AFRL-IF-RS-TR-1999-216
Final Technical Report
October 1999

OPTICAL MEMORY APPLICATION STUDY

Synectics Corporation

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AFRL-IF-RS-TR-1999-216 has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Oct 99	Final Mar 96 - Mar 98

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
OPTICAL MEMORY APPLICATION STUDY	C - F30602-96-C-0051 PE - 63726F PR - 3192 TA - 00 WU - 13
6. AUTHOR(S) Joseph J. Riolo and James R. Wilson	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Synectics Corporation 111 E. Chestnut St. Rome NY 13441-4114	8. PERFORMING ORGANIZATION REPORT NUMBER N/A
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFRL/IFED 32 Brooks Rd Rome NY 13441-4114	10. SPONSORING/MONITORING AGENCY REPORT NUMBER AFRL-IF-RS-TR-1999-216

11. SUPPLEMENTARY NOTES

AFRL Project Engineer: Albert A. Jamberdino, IFED, 315-330-2845

12a. DISTRIBUTION AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT *(Maximum 200 words)*

The objective of this effort was to determine the potential user-base of the three-dimensional (3-D) volumetric memory (VM) technology currently under development at AFRL, Rome Research Site. A secondary objective was to determine the system characteristics this storage technology must possess to ensure successful transition into current and emerging weapon systems. The technical approach followed included a survey of potential storage technology users. The results summarized in this report support the high potential viability of this technology while helping to establish functional, physical and economic requirements needed to guide its development over the next few years.

14. SUBJECT TERMS	15. NUMBER OF PAGES
volumetric memory, computer storage, storage and retrieval	76
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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1.0 INTRODUCTION

This document is the Final Technical Report (CDRL A002) for Contract No. F30602-96-C-0051 entitled "Optical Memory Application Study." This was a 24-month effort that ran from 20 March 1996 to 31 March 1998. Synectics Corporation was the prime contractor and had Computing Devices International (CDI), Pacific-Sierra Research (PSR), L3 Communications (L3), Raytheon E-Systems (Raytheon), and Rising Edge Technologies, Inc. (RETI) as subcontractors on the effort.

Synectics submitted a proposal abstract, in response to BAA 94-02-PKPB (Optical Memories), for the performance of an Optical Memory Application Study. It addressed the dominant theme of the BAA, which was to increase the knowledge and understanding of the broad range of capabilities in support of volumetric memory technology to meet storage and retrieval requirements for the late 1990s.

The storage and retrieval of large volumes of data places heavy demands on the associated data storage subsystems. Unfortunately, an inverse relationship currently exists between the access and data transfer times of memory storage subsystems, and their data density and cost per bytes. As a result there is no mass storage alternative, which is both suitably fast and cost-effective for the full range of potential applications. Three-dimensional volumetric memories (3DVM) hold promise for solving this problem. These memories offer the possibility of faster access times, larger storage capacities, smaller size, higher throughput, and lower cost per byte.

If these possibilities become real, volumetric memories may offer a nearly ideal mass storage alternative for ground-based, airborne, and space-based applications. Each potential application, however, has its own set of requirements, including size and weight constraints; power consumption and cooling; and capacity, access, and throughput characteristics. In order to ensure that these new memories meet the form, fit, and function of the applications, it is important to determine the design parameters early in the development life cycle.

2.0 OBJECTIVES

The objective of our effort was to determine the potential user base of the volumetric memory technologies currently being developed at the AFRL Rome Research Site, and to determine the characteristics, which these technologies must possess in order to make them suitable for use.

The study consisted of three tasks. In the first task Synectics assembled a comprehensive set of informational materials which described the volumetric memory technologies being developed, as well as evaluation criteria which were used for gathering mass storage requirements.

Secondly, Synectics made these materials available to a wide range of DoD and commercial mass storage users and solicited their inputs on form, fit, and function for an operational volumetric memory.

Finally, Synectics condensed the results of this broad survey to:

- Determine the broad application areas.
- Determine the overall design parameters for each application area.
- Make recommendations suitable for guiding the technology development.

3.0 TASK 1 - STUDY DESIGN

During the study design, Synectics performed three primary activities.

- We assembled a comprehensive set of informational materials, which were distributed to potential users of the memory. These materials described the current state of the art; basic theory of operation; projected and achieved performance; and projections of development timelines, technology maturation, and system characteristics. These informational materials were in the form of briefings, technical reports, and references to additional information.
- We identified a broad range of potential users and the organizations, which play key roles in the development and planning for those applications. These included ground-based, airborne, and space-based applications, with an emphasis on Air Force users. Users outside of the Air Force were also identified, including broader DoD and commercial arenas.
- We determined the information that must be gathered from each user in order to allow us to determine the characteristics, which will be required of an operational volumetric memory. Data requirements will be captured in the form of questionnaires, interview guidelines, and subcontract statements of work.

4.0 TASK 2 - DATA COLLECTION

During the data collection, Synectics entered into subcontracts with a wide range of potential users, as identified in Table 1. Synectics, through its longstanding history of work in the DoD

and intelligence arenas, has established working relationships with a broad spectrum of potential memory users.

Each of the companies was provided with the informational and evaluation materials and was asked to provide critical information on the following items.

- ❑ Candidate memory applications.
- ❑ Required performance characteristics, including data access rate, data transfer rate, and storage capacity.
- ❑ Required physical characteristics, including size, weight, and shape.
- ❑ Required environmental characteristics including shock tolerance, vibration tolerance, radiation tolerance, and power and cooling requirements.
- ❑ Required functional characteristics such as rewriteability, eraseability, and others.

Each company was required to supply a set of information, as determined under Task 1. In addition, each was asked to provide a write-up of their view of the technology, its strengths and weaknesses, as well as recommendations not covered by the standard set of data collection materials.

Table 1. Survey Participants

COMPANY	SYSTEMS/APPLICATIONS
L3 Communications	Space and ground communications, medical archive systems, information security, naval communications systems
Pacific-Sierra Research	Airborne sensor systems, including Common Aperture Multispectral Sensor (CAMS), AAD-5, Open Skies Follow-On Sensor Evaluation Program, and others
Computing Devices International	Airborne, space-based, ground-based, and shipboard sensors and data processing systems
Rising Edge Technologies, Inc.	Data storage systems designed to enhance the capabilities of host computers and applications while safeguarding important data
Raytheon E-Systems	Joint Services Image Processing System (JSIPS), space-based sensor systems, other ground stations

5.0 TASK 3 - ANALYSIS AND RECOMMENDATIONS

5.1 TECHNICAL ASSESSMENT

It is well known that today's defense and commercial computer applications have desperate needs for high-speed and huge capacity data storage. The industry is working to fill that need which grows daily. A new technology like 3DVM, combining faster access times, larger capacities, and smaller volume, is a great improvement in raw data storage power. However special application constraints like temperature, weight, and power limitations must be satisfied as well.

This study, performed by five companies and covering nearly a dozen specific applications, shows the positive viability of 3DVM with respect to the characteristics of real-world applications. It points out development directions that can make 3DVM useful in both static and mobile environments.

3DVM is a fundamental improvement over current technologies. In future years, it should blossom and branch into whole families of devices as ubiquitous as magnetic media.

This effort consisted of an evaluation of 3DVM against commercial and defense applications. The results, summarized and discussed in the following material, strongly support the high potential viability of this technology while helping to establish the functional, physical, and economic requirements, which will guide its development over the next few years.

The developing technology of 3DVM was evaluated for its applicability in several specifically defined computing environments. Each study report describes the subcontractor's particular area of interest and the current technologies in those areas, and was used as the basis for comparison against the 3DVM evaluation.

This following summaries concentrate on the conclusions drawn by the subcontractors concerning 3DVM's place in the future of their enterprises. Tables and diagrams from the reports are not duplicated in this summary.

5.1.1 COMPUTING DEVICES INTERNATIONAL (CDI)

The next generation of Joint Surveillance Target Attack Radar Systems (JSTARS) aircraft being jointly designed by CDI and Northrup Grumman will have advanced mission critical mass storage requirements. Three main mass storage elements are:

- 400 megabytes of RAM in the radar signal processing computers.
- 5 computers, each with a group of 4, 1-gigabyte disks attached.
- 18 workstations with 1, 1-gigabyte disk each (may add a second disk).

The current combined storage of 23 gigabytes (increased to 41 gigabytes if all workstations are upgraded) in 23 computers is deemed insufficient to handle required, additional collateral information for sensor analysis. Greatly increased volumes of collateral information will enable operators to interpret the information in new and qualitatively more effective ways. In addition to the three kinds of existing storage listed above, the new aircraft are planned to have a high bandwidth RAID (Redundant Array of Independent Disks) system to record sensor data. 3DVM may be a viable substitute for the RAID.

The RAID, or its equivalent data storage component, will have a minimum sustained data rate of 70 megabytes/second; however, 160 megabytes/second is preferred. Its total capacity must be at least 72 gigabytes. Data storage capacity of 2 terabytes would enable recording an entire 8-hour mission.

The main requirements include approximately 216 gigabytes for each of 5 central computers and 9 gigabytes each for 5 workstations. Critical requirements are high performance, low error rate, high altitude operation, tolerance to vibration, temperature, and shock.

3DVM risk issues that need to be addressed during the development phase are loss of data at high temperatures, long access time for consecutive fetches, and non-removability. Issues such as interfacing and removability are separate from the 3DVM technology. They are appropriately addressed as packaging issues and are understandably unpolished in a laboratory setting.

The JSTARS program is particularly ripe for advances in data storage capacity technology, so 3DVM is an attractive candidate for technology insertion. Once 3DVM has overcome the stated technical problems and a transparent interface with the host systems becomes available, it can successfully enter the JSTARS market. 3DVM will be highly cost-competitive with technologies that are currently being developed in magnetic and optical media.

5.1.2 PACIFIC-SIERRA RESEARCH (PSR)

PSR performed the most specific study in the group, focusing on the Wedge Imaging Spectrometer (WIS) for Unmanned Air Vehicle (UAV) and Common Aperture Multispectral Sensor (CAMS) systems.

Multiple sensor systems like these have particularly high requirements for both speed of recording and total storage capacity. Their operating environments place unusual restrictions on cost and physical characteristics. Equipment used in unmanned missions is at higher risk and must be correspondingly less expensive. The compact UAV platforms place very specific limits

on size, power, cooling, and weight. Throughput limitations on current storage devices have caused some available data to be filtered out and not stored.

3DVM's medium to high temperature sensitivity is an important shortcoming in this environment. The volumetric storage must be easily and transparently interfaced to the host processors. The new technology should demonstrate its ability to scale up so that storage-intensive, isolated systems like those in a UAV can access many terabytes. There is concern that data near the surface of the cube will interfere with addressing and with access to data deeper within it.

Quoting from PSR's report, "It appears that 3D 2-photon memory devices have the potential of alleviating the data throughput imposed limitation associated with both the WIS and the CAMS."

3DVM would then free processor power for other pre-processing in place of the current data filtering activity. It would also enable ground-based computation of frame-to-frame correlation to stabilize the image rather than having to use processor resources on board to save data storage.

Bulk data storage organization in the 3DVM is very similar to the way data is collected by the WIS so the sensor/recorder interface could be much simpler.

An exciting possibility not mentioned by other studies is that some image processing may be performed directly within the 3DVM, for instance, by writing the data in along certain axes and then reading out the data from another direction. Thus, image coherence in this other direction could be exploited.

5.1.3 L3 COMMUNICATION (L3)

Airborne and space environments increasingly require high data rate, and high capacity data storage systems. Space-based requirements differ slightly from their airborne counterparts due to different physical characteristics and longer missions.

Particular comparative requirements were abstracted from Table 3 in L3's report.

- ❑ Space - Capacity minimum 100 terabytes, multiple gigabytes/second, no convection cooling.
- ❑ Airborne - Capacity minimum 200 gigabytes, must be non-volatile with archiving capabilities, severe temperature variations, must be low cost and replaceable.

Magnetic tape and semiconductor memories such as Dynamic Random Access Memory (DRAM) are the current technologies in use for data storage aboard aircraft and spacecraft. They reflect the current best solutions for low cost, non-volatility, high capacity, high data rate, and severe mechanical conditions. A key element for acceptance of a new data storage technology is

the ability to use existing interfacing methods and protocols, in effect hiding the new technology from the system it will support.

Data storage in airborne systems is required to be non-volatile and removable. In addition it is subjected to conditions of temperature extremes, severe vibration, and acceleration. If 3DVM is to be used effectively in airborne systems, these issues will need to be addressed. 3DVM's current temperature limits will need improvement, as well as its packaging. In order for 3DVM to be a viable option in this market, the packaging will need to be designed to accommodate the vibration and acceleration conditions encountered in the airborne environment.

3DVM provides improved capacity and data access. It promises much better size and cost than DRAM. At one terabit per cubic centimeter, the fundamental data storage medium, if it were fabricated in a cube only 10 cm on an edge, would easily accommodate 100 terabytes as opposed to an estimated 12 million common DRAM (64 megabyte) chips. Mechanical and thermal limitations will be overcome.

The rate of projected improvements in 3DVM is much more in line with the increasing demands of space and airborne applications than those of competing technologies, specifically including the projected increases in DRAM capacity.

5.1.4 RAYTHEON E-SYSTEMS

This study considered the role of 3DVM in Joint Services Image Processing System (JSIPS) and all related tactical systems for processing and display functions. It also considered the Risk Reduction Image Processor (RRIP) for multiple platform, multiple type images.

Imagery processing and, particularly tactical imaging, have unique digital storage constraints. They must input, process, and output (display) image data from many sources and in differing formats. Their relatively low downlink rates imply increased storage capacity is required to bridge the longer transmission times.

Tactical imagery uses 95-gigabyte tape recorders and provides a separate archive copy. Common Image Processor (CIP) information, primarily from radar, is very similar to other imaging needs, but more storage capacity could expand the information obtained from each image. Higher speed computers with greater storage capacity could enable a choice of different and more efficient algorithms to actually increase the information content of displays for radar processing.

The only current deficiency in 3DVM technology for tactical imagery processing is some loss of data during high temperature operation. The sensitivity of its moving mechanical, positioning, and registration parts to vibration and shock will be eliminated in commercially packaged versions of 3DVM. Tactical imagery processing needs storage units operating in parallel. The laboratory version of 3DVM is not so configured, but there is no inherent impediment to such an arrangement.

Current systems meet the needs of these image-processing areas, but the capacity requirement is always rising. System capacities must continue to grow. 3DVM, by replacing magnetic tape operations, would provide unattended operation thus relieving the current human intervention, device multiplexing, and tape cartridge handling. The result will be more reliable and much less costly. 3DVM can also eliminate the need for short-term archiving by keeping all needed data on-line.

3DVM has a large potential in both military and commercial systems. Packaged for robust, scalable operation and COTS distribution, 3DVM will supply needs that cannot be currently met by semiconductor technologies.

5.1.5 RISING EDGE TECHNOLOGIES, INC. (RETI)

RETI focused on the digital storage subsystem market with special emphasis on document imaging and medical imaging. It also included consideration of film editing, video editing, and multimedia markets.

Among the identified market areas, each has different data storage requirements. A wide variety of storage technologies are in high use in these markets, ranging from magnetic tape to magneto-optical (M-O) disk.

From a figure of $600 million in 1996, the electronic data capture (EDC) industry has grown at an annual rate of 50%.

Medical imaging has higher requirements for reliability and redundancy. Improved customer service and drastically lower costs can be achieved through improvements in computer systems for data repositories, interface engines, master patient indices, and work flow management.

Media content development is a broad market, which includes film editing, video editing, and multimedia. All of the sectors of the media content industry need very high performance because their images are increasingly detailed and information dense and because those images are replicated hundreds of thousands of times for animation. Digital editing is only able to replace linear cut and splice film techniques through the availability of all of the images on-line.

In document imaging, raw capacity is less important than quick retrieval because the actual amount of relevant or useful information present on each retrieved document is typically small while the number of documents retrieved may be very high.

More comparisons between 3DVM and the other data storage media would be beneficial for evaluating this technology in light of the fluid development in the various imagery industries.

3DVM's data density, access time, and throughput stack up well against competing technologies. With respect to these imagery industries, 3DVM was found to be adequate, but generally not

better than other forms, in capacity, cost, power, size, and weight. Its prime selling point in this arena is its remarkable growth potential.

3DVM can enter the document, media content, and medical imaging markets. 3DVM will be a strong competitor as its size and cost become more competitive. For the medical imaging market specifically, the assured data retention in 3DVM will be extended to 7–10 years, or more.

5.2 STUDY SUMMARY

The 3DVM operating temperature range must be expanded for any use other than ground-based, non-mobile systems. It must be smaller, lighter, use less power, and be fully functional under severe vibration and shock. It must use current standard interfacing methods such as SCSI, High Performance Parallel Interface (HIPPI), or Fibre Channel. The system should also be transparent to the data management functions of the target systems. 3DVM has high potential in all of the fields studied and is already a close fit for several of them.

A characteristic of 3DVM that no study mentioned is its lack of vulnerability to local magnetic fields or electromagnetic pulse (EMP). Perhaps the heavy use of other optical media has diluted the perceived importance of this feature.

6.0 CONCLUSIONS AND RECOMMENDATIONS

In a very broad spectrum of likely application areas, 3DVM has shown a high potential for viability. However, it has also pointed up the importance of several issues, which must be addressed before the potential turns into a commercially successful reality. Many of the applications for which 3DVM is most needed are mobile applications where there are major requirements for physical stability and robustness. For instance, the current laboratory development stage of 3DVM does not easily withstand high intensity vibration. Yet, 3DVM possesses some characteristics, notably a resistance to ambient magnetic fields and EMP that make it more rugged than its magnetic media competitors.

Despite the great capacity and fast access of 3DVM, some applications require much more on-line storage than a single 3DVM. It will be necessary for those applications to operate multiple 3DVM units simultaneously, or to scale the base unit to larger dimensions, or both.

The required enhancements and the applicable components are summarized below.

1. **Data stability at higher temperatures.** In applications such as JSTARS the 3DVM will need to operate at greater extremes of temperature. In some applications, it may be adequate to use a simple and efficient way to cool the assembly.

2. **Interfacing.** The requirement that the 3DVM (or any storage medium) be connected transparently to the host is well supported by the current laboratory prototypes and the interface similarity among them and other media such as hard disk. 3DVM will not require refreshing, which avoids some interfacing burden. It must use current standard interfacing methods such as SCSI, HIPPI, or Fibre Channel.

3. **Weight, size, power, and cost.** The packaging must not only conform to physical constraints, but it must also be easily removed. In an analogous way to the drive-diskette arrangement, the ability to leave the cube reader in place and simply remove and replace the cube would be beneficial in applications such as fighter aircraft. The device must follow current drive power requirements in order to be accepted in the community. Size and weight also play an important role. The 3DVM must fit into a standard drive compartment and weigh no more than a current drive. In order for the 3DMV to compete with COTS products, it must have a competitive cost per megabyte.

4. **Vibration and acceleration.** As long as data addressing is accomplished by moving mechanical parts, vibration, acceleration, and recalibration will be critically sensitive.

5. **Parallel operation.** The ability to gang multiple 3DVM units together, when fully developed, will support the ultra-high capacity needs of some specialized applications. Individual units should be able to run side-by-side in a very compact configuration. Additionally, the volume of a unit may be scaled upward with the data capacity increasing as the cube, not just the square, of the increase.

6. **Non-volatile operation.** 3DVM data are inherently non-volatile as long as the temperature range is controlled. Particularly for medical applications, a 7–10 year assured data retention must be achieved and demonstrated.

This report has shown the long-term viability of and broad areas of application for, 3DVM, and it has discussed the parameters of such memory for each application area.

7.0 ACRONYMS

3DVM	Three-Dimensional Volumetric Memories
AFRL	Air Force Research Laboratory
BAA	Broad Area Announcement
CAMS	Common Aperture Multispectral Sensor
CIP	Common Image Processor
COTS	Commercial Off-The-Shelf
DoD	Department of Defense
DRAM	Dynamic Random Access Memory

EDC	Electronic Data Capture
EMP	Electro-Magnetic Pulse
HIPPI	High Performance Parallel Interface
JSIPS	Joint Service Imagery Processing Systems
JSTARS	Joint Surveillance Target Attack Radar System
M-O	Magneto-Optical
OMAS	Optical Memory Application Study
RAID	Redundant Array of Independent Disks
RAM	Random Access Memory
RRIP	Risk Reduction Image Processor
SCSI	
UAV	Unmanned Air Vehicle
WIS	Wedge Imaging Spectrometer

APPENDIX A -
COMPUTING DEVICES INTERNATIONAL REPORT

Optical Memory Application Study

White Paper
developed by

Computing Devices International
8800 Queen Avenue South
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under contract to the
Synectics Corporation

1. Objective

The objective of this white paper is to determine the current and projected near term (1-5 year) applicability of 2-photon 3-D optical memory technology to the Joint STARS platform. We will also describe the form fit and function requirements of this application as it constrains the application of this technology.

2. Background

The reason for considering 2-photon 3-D optical memory is to attempt to find a memory type that is simultaneously fast and massive in capacity and inexpensive. All existing memories can be optimized for any two of these parameters, but not all three.

Computing Devices International currently is the supplier of all the mission critical mass storage devices on the Joint STARS aircraft. We have worked with Northrop Grumman through several studies and RFI/RFP cycles as they work to define the storage solution they wish to implement for the next generation aircraft. Although that new configuration is not precisely defined yet, we will share in this paper our understanding of the most likely configuration and the customerís current priorities.

3. Current and anticipated Joint STARS mass storage requirements and deficiencies

3.1 Current requirements

The present Joint STARS aircraft uses large memory systems in three areas: RAM in the RADAR signal processing computers, disks attached to central computers, and disks attached to individual workstations. The RAM is approximately 400 MBytes. The five (5) central computers each use one group of four 1 Gigabyte disks. The eighteen (18) operatorís workstations each use one 1 Gigabyte disk, with provision for adding a second disk to each station.

3.2 Current deficiencies

Storage Capacity

There is a desire to provide much more collateral information to the operators to assist them in their efforts to interpret the information that they are receiving in real time. This requires greatly increased storage capacity.

Architecture

This system uses a LAN to distribute all sensor data through the central computers to the individual workstations. The LAN is currently a performance bottleneck. It is unable to support distribution of overlays, underlays and other collateral data, such as high resolution still imagery or video to the individual workstations.

3.3 Projected requirements

3.3.1 General

Computing Devices and the prime contractor have defined near term solutions to the above deficiencies using currently available technologies. The memory of the Joint STARS aircraft is expected to include the same three (3) types of memory as is presently used, with the addition of a very high bandwidth RAID system to record raw

sensor data. The interconnect topology of these memories is the same as in the existing system.

The majority of the specification changes are expected to direct the use of COTS systems. The customer expects to use nearly pure COTS in order to take advantage of the low acquisition cost and expected ease of migration to follow-on systems. The RAID system is an entirely new memory requirement, which will also be COTS. It is desired to have a sustained data rate of at least 70 megabytes/sec (160 megabytes/sec is preferred) and is to utilize a Fibre Channel interface. The total capacity of this RAID is to be at least 72 gigabytes. This capacity point simply echoes the available COTS systems, much higher capacity would be preferred. The Joints STARS system could utilize as much as two (2) 2 terabytes, which would permit recording an entire eight hour mission, as opposed to just portions of a mission.

In addition, there is a desire to add other memory types to support maps, UAV video, SAR data, and data from other sensors. This requirement is not well defined at this time but could reasonably be expected to be in the many hundreds of gigabytes up to a few terabytes.

3.3.2 Specific

The requirements for the new memory systems have not been finalized. We believe that they are reasonably represented by the information in the tables below. These requirements reflect what we believe can be met with todayís COTS technology.

Memory Unit Specific Requirements

	RAM	Operatorís Workstation	Central Computer	RAID
Capacity (GBytes)	1 to 2	≥2 removable modules, each up to 9GB	24 removable modules, each up to 9GB	≥ 72
Performance	5 ns random access time	> 3 MB/sec, sustained	>12 MB/sec	≥ 70 MB/sec, sustained, future ESAR will need ≥ 260 MB/sec
Error Rate	not specified	≤ 1 in 10^{13}	≤ 1 in 10^{13}	≤ 1 in 10^{13}
Interface	processor bus	SCSI, wide, FAST, differential	Multiple SCSI, wide, FAST, differential	Fibre Channel Arbitrated Loop
Size	Note 1	19î Rackmount ~15î deep ~7î high	19î Rackmount ~19î deep ~36î high	19î Rackmount ~30î deep ~11î high
Weight	Note 1	< 30 pounds	<300 pounds	< 100 pounds
Power	+5 Vdc	110 Vac	110 Vac	110 Vac

Notes: 1. The RAM is not separately packaged, it is integrated on the Signal Processor boards being considered.

General Environmental Requirements

Altitude (operational)	decompress from 8,000 ft to 42,000 ft in 5 seconds, then operate at 25,000 ft for 2.5 hours
Vibration	10-40 Hz .0005g^2/Hz 40-70 Hz -4.9 dB/oct. 70-200 Hz .0002g^2/Hz
Operating Shock Crash Shock	6gís, 11 ms <9gís
Temperature operating non-op	 0 to +35 C -30 to +66 C
Humidity	<95%, non-condensing

It is important to note that each of the non-volatile memory media is required to be removable so that classified material can be removed from the aircraft. This requirement is expected to remain unchanged in the future.

The memory media in the operatorís workstation and central computer are required to be interchangeable so as to reduce the logistics support requirements. It is preferred that these are also interchangeable with the memory media in the RAID.

4. Applicability of 2-photon 3-D optical memory to Joint STARS

4.1 Current operational shortfalls

The papers provided, along with our background knowledge, were used to consider how to apply the 2-photon 3-D optical memory systems. Because this is an active research area, we understand that many different features of the memory are being examined and improved. We feel that there are a number of issues that stand out as particular risk areas requiring resolution before this optical memory can be considered as a replacement for the current Joint STARS memories:

4.1.1 Non-volatility

The available materials are either unstable or marginally stable at room temperature. Although the aircraft normally has a ìshirt sleeveî environment, many factors cause the memory to be exposed to higher temperatures. These include the natural temperature rise within equipment bays, the need to operate occasionally with less than ideal cooling system operation, and the ability to operate after a non-operational period exposed to high temperatures. (Imagine the aircraft parked on the ramp in Riyadh with engines off and no cooling air for a few hoursÖ). The ability of the memory to tolerate hot storage conditions without losing the programmed memory will be important to demonstrate.

4.1.2 Access time

The optical memories have very fast transfer rates and fast access times to a given region in memory, but cannot provide this fast access to consecutive fetches that may be in widely separated address regions. The optical memory then cannot be considered as a RAM replacement. (Although the optical memory could match RAM performance

over a limited address span, the infrastructure required to implement the optical memory dwarfs the simplicity of a RAM for a small memory capacity such as a cache).

Access times across large address spans for the optical memory are comparable to, or superior to the access times of the existing secondary (disk) storage media.

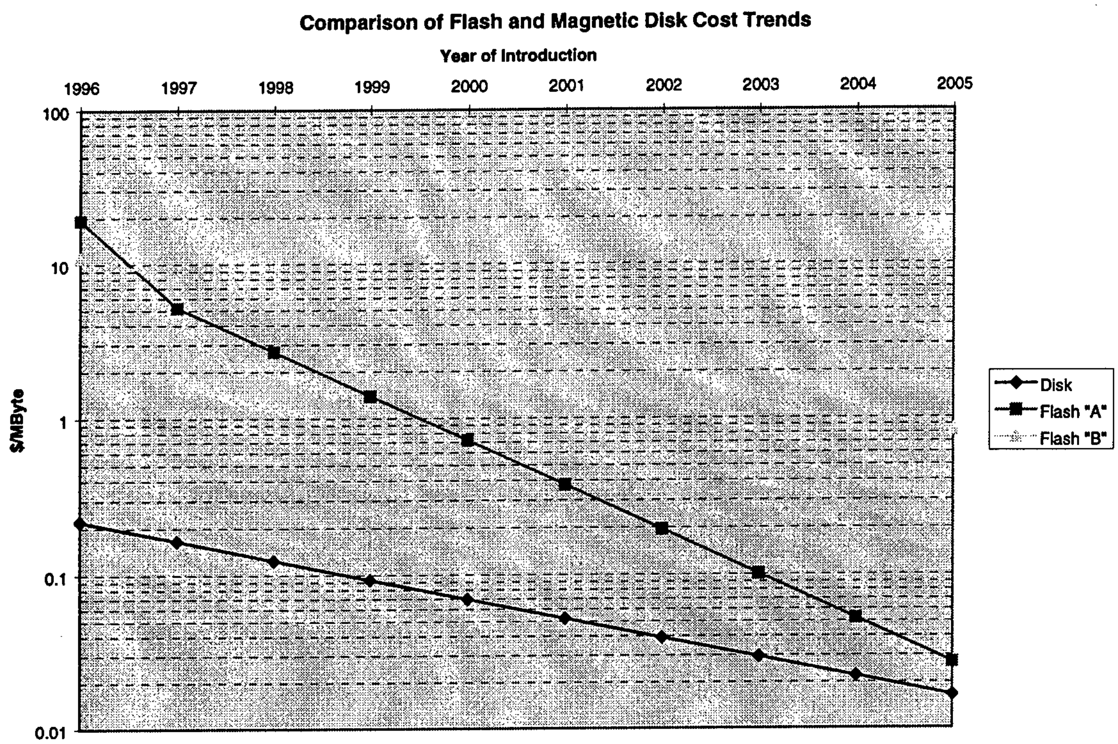
4.1.3 Removability

The techniques for providing appropriate packaging, re-calibration and other automatic adjustments to support easy operator removal and replacement of the actual storage media have not yet been considered in the provided research material. Significant work is expected to be required to be performed to provide easy interchange of media.

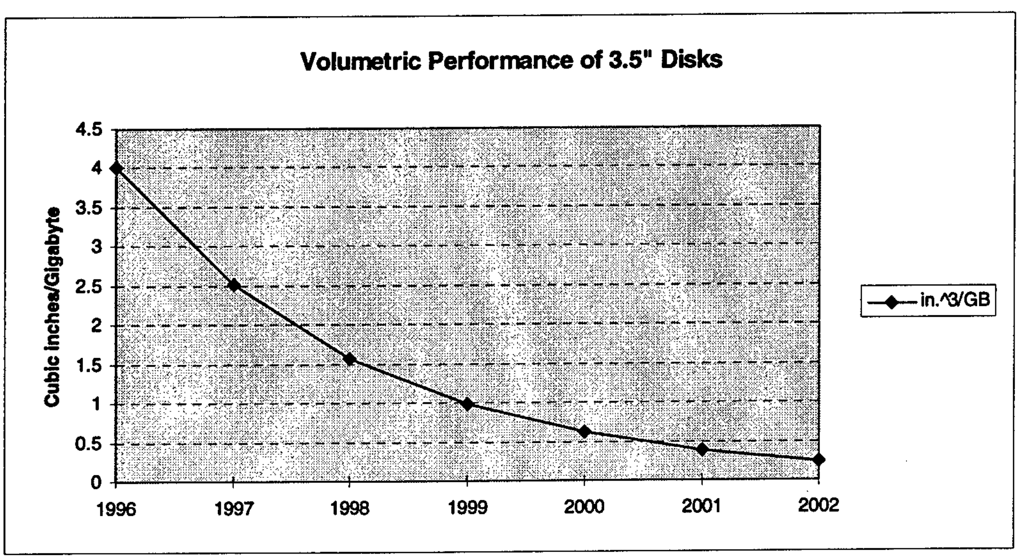
4.2 Future operational needs

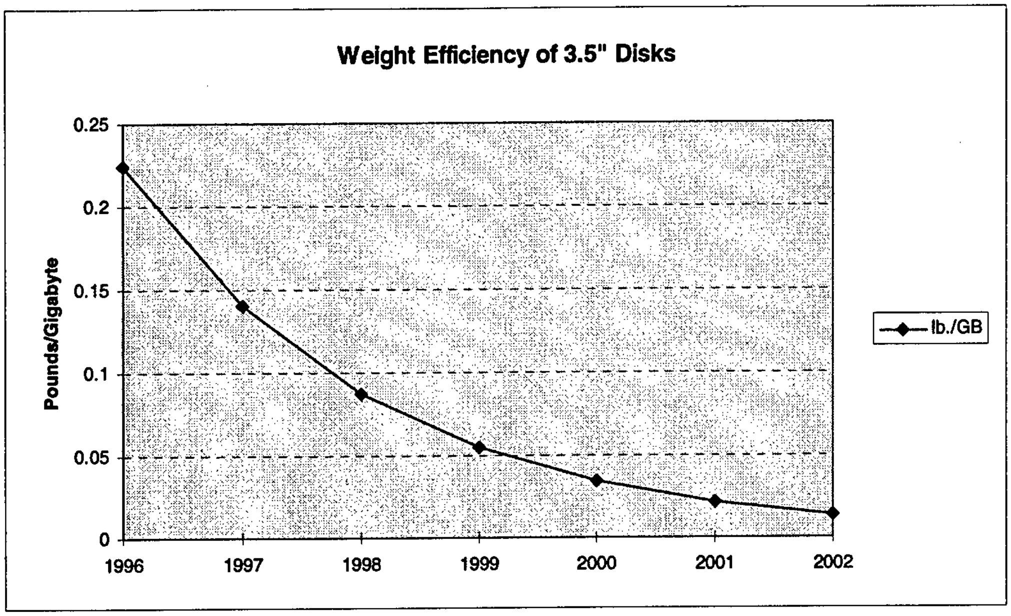
The 2-photon 3-D memory is an attractive possible candidate for both the long term massive memory used to store related maps and video as well as the sensor data recorder. Each of these applications needs enormous volumes of data, accessed at high sustained rates.

In order to be considered for these roles, this new memory must be able to intercept the existing memory technologies as they advance under their own research programs. Magnetic disk and tape are the leading contenders at this time for high data rate combined with high storage capacity. Optical disk in the form of DVD jukeboxes will be a powerful contender for the modest data rate, data warehouse applications. Solid state (Flash EPROM) is a very attractive mass memory alternative, although it is quite costly now. The figure below shows cost trends taken from various trade sources for commercial magnetic disk and solid state media. At the projected year of introduction, the 2-photon 3-D memory must be planned to be cost compatible, even if not immediately competitive, with these established technologies. The Flash ìAî curve is an optimistic price projection, and the Flash ìBî curve is a more conservative price projection.



Additional indices that can be used to guide the introduction of this new technology are its volumetric and mass efficiencies. The figures below show the cubic inches per megabyte and the pounds per megabyte of existing COTS disk technology. As for cost, the 2-photon 3-D optical memory must be planned to be competitive or superior to these indices at the planned time of introduction.





(Note that these three indices represent commercial products including the memory and all necessary host interface electronics.)

4.3 Transitional requirements

Assuming that the memory technology is competitive, based upon indices such as those illustrated above, and that it is reasonable to believe that it could be made to meet the environmental requirements, then it should be a attractive candidate for a possible technology insertion.

In order to transition from ìconceptî to ìimplementationî on the Joint STARS aircraft, it is important to understand two (2) key elements: (1) The Joint STARS prime contractor normally inserts new technology as part of a major ìblockî change when many changes are being made at the aircraft. This makes it much more difficult to insert a change between blocks. However, this does make it possible to understand the schedule for future block changes and to aim for insertion on that schedule. Computing Devices estimates 3-4 block upgrades to occur within the next 10-15 years. (2) The actual transition effort would be expected to pass through a technology assessment at the Advanced Development Lab, an integration demonstration at the System Integration Lab, and then finally a demonstration on board the actual aircraft through the Aircraft Integration Lab.

The single most important feature that must be provided to transition this new memory type to an event such as a trial flight, is the host interface. The less the new memory causes a disruption to the existing operating system, device drivers, BIT, cable plant and the like, the more likely it will be to be seriously considered as a replacement. The memory must be able to appear to the host as if it were the same as the memory being replaced. Thus, for example, if a refresh cycle is required due to destructive readout, this must be hidden from the host. Similarly, if the minimum addressable memory region is a large page or special measures must be taken to perform error detection and correction steps, these also must be hidden from the host.

4.4 Other Systems/Summary

The Joint STARS program is one of the most data storage hungry systems of the unclassified programs we are working on at this time. It is the best opportunity for the insertion and demonstration of the 2-photon 3-D optical memory technology that we are aware of. However, the limitations identified in Section 4.1, need to be addressed by Synectics in order to proceed through the transition phases of Section 4.3. The requirements herein are bound by todayís technology. The application of technologies such as the 2-photon 3-D optical memory present opportunities to expand the bounds of these requirements.

APPENDIX B -
PACIFIC-SIERRA RESEARCH REPORT

PSR Report 2722

APPLICATION OF 2-PHOTON 3D OPTICAL MEMORY TECHNOLOGY TO AIRBORNE MULTISPECTRAL SENSORS

C. S. Kaufman

August 1997

Purchase Order Number 97-133

Sponsored by
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CONTENTS

FIGURES

Section 1
INTRODUCTION

The objective of this effort was to determine the current and projected (1-5 year) applicability, as well as "form, fit, and function" requirements, of 2-photon 3D optical memory technology as applied to two of specific systems. This information will be utilized by Synectics Corporation to evaluate the potential of this technology and to provide guidance to the development process. Specific system to be addressed in this report are the Wedge Imaging Spectrometer (WIS) Hyperspectral Imaging sensor for Unmanned Air Vehicle (UAV) applications, and the Common Aperture Multispectral Sensor (CAMS).

The storage and retrieval of large volumes of data places heavy demands on the associated data storage systems. Unfortunately, an inverse relationship between the access and data transfer times of memory storage subsystems, and their data density and cost per byte currently exists. As a result there is not currently a mass storage alternative which is both suitably fast and cost effective for the full range of potential applications. Other factors, such as the operational environment, power and cooling requirements, and form factor, also impact the technology's suitability for any particular application.

Three-dimensional (3D) optical memories appear to hold promise for solving many of these problems. Optical memories offer the promise of faster access times, larger storage capacities, smaller volumes, higher throughput rates, and lower cost per byte. If these promises are kept, optical memories may offer a nearly ideal mass storage alternative for ground based, airborne, and spaceborne applications. Each potential application, however, has its own set of requirements, including size and weight constraints, power consumption and cooling, and capacity, access, and throughput characteristics. In order to ensure that optical memories meet the "form, fit, and function" of the applications which stand to benefit most, it is important to determine these parameters early in the technology development life cycle.

This report is divided into 4 sections. The first section is this introduction. The second section provides a brief description of the two systems and their current and projected data storage requirements. Section 3 identifies data storage limitation of the current systems and requirements for a 2-photon 3D optical memory device. Section 4 provides recommendations for the development of 3D 2-photon memory devices for these applications, and potential addition applications for this the of storage device.

This work was performed for Synectics Corporation in Rome, NY, and the direction of Mr. Brad Rogers.

Section 2
SENSOR OVERVIEW

2.1 WEDGE HYPERSPECTRAL SENSOR (WIS)

2.1.1 WIS Functional Description

WIS in an imaging sensor that collects ground imagery from an airborne platform. Typically, this sensor is used to collect reconnaissance or surveillance imagery at low to medium altitudes (less than 6000 ft.). The current trend is to utilize an unmanned air vehicle in support of tactical operations, see Figs. 1 and 2. A block diagram for a typical WIS system implementation for a UAV is shown in Fig. 3.

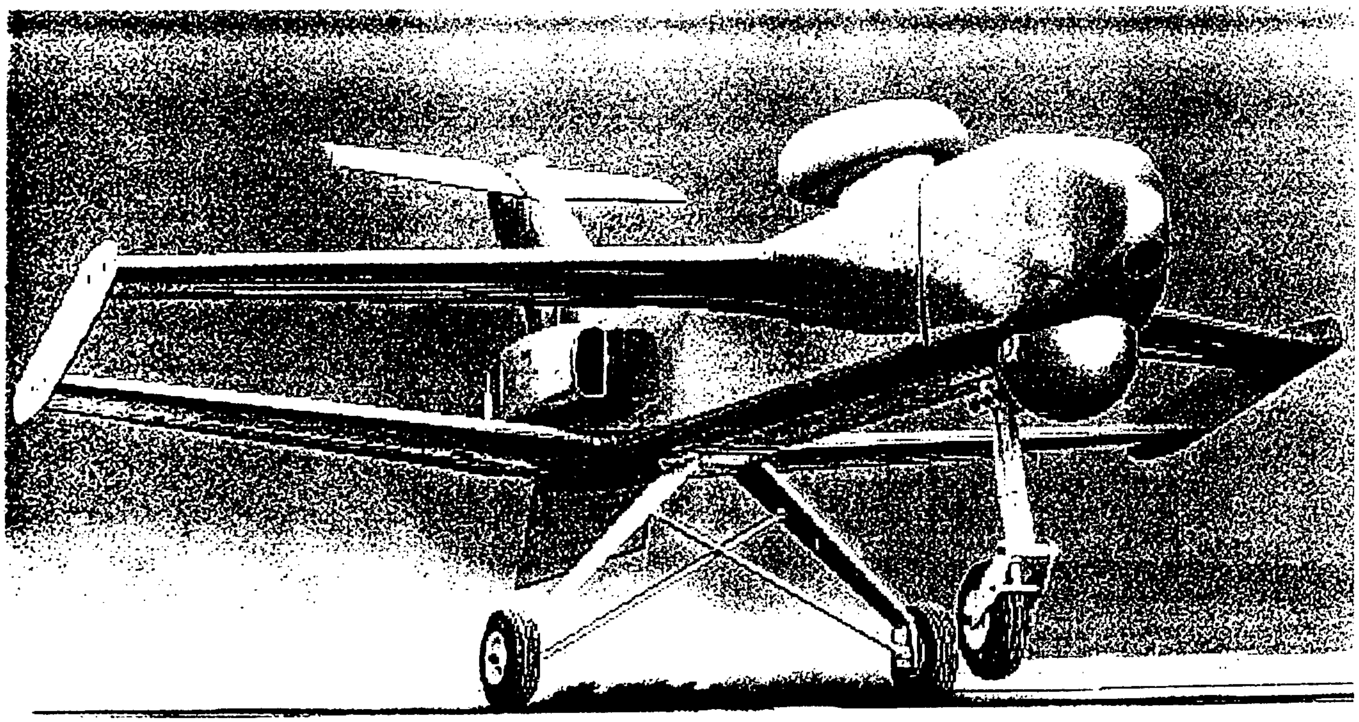

Figure 1. Outrider II tactical UAV (TUAV).

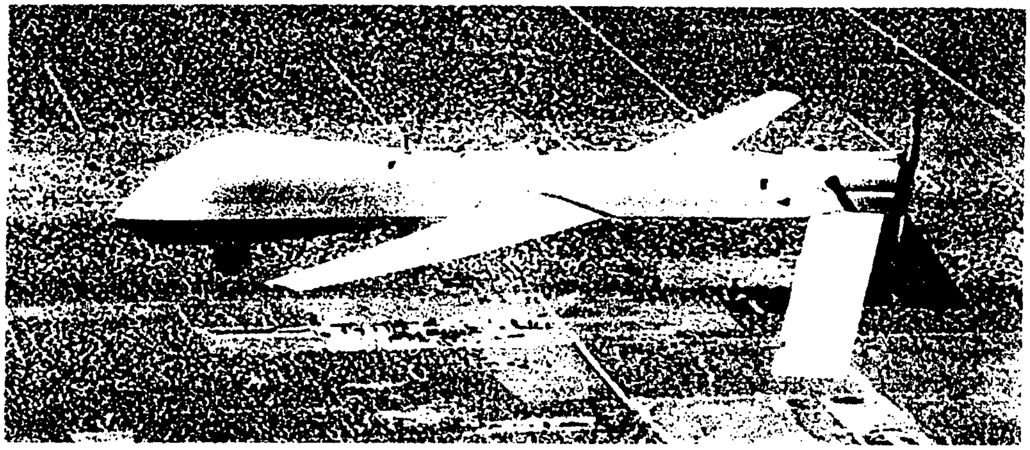

Figure 2. Predator medium range tier II UAV.

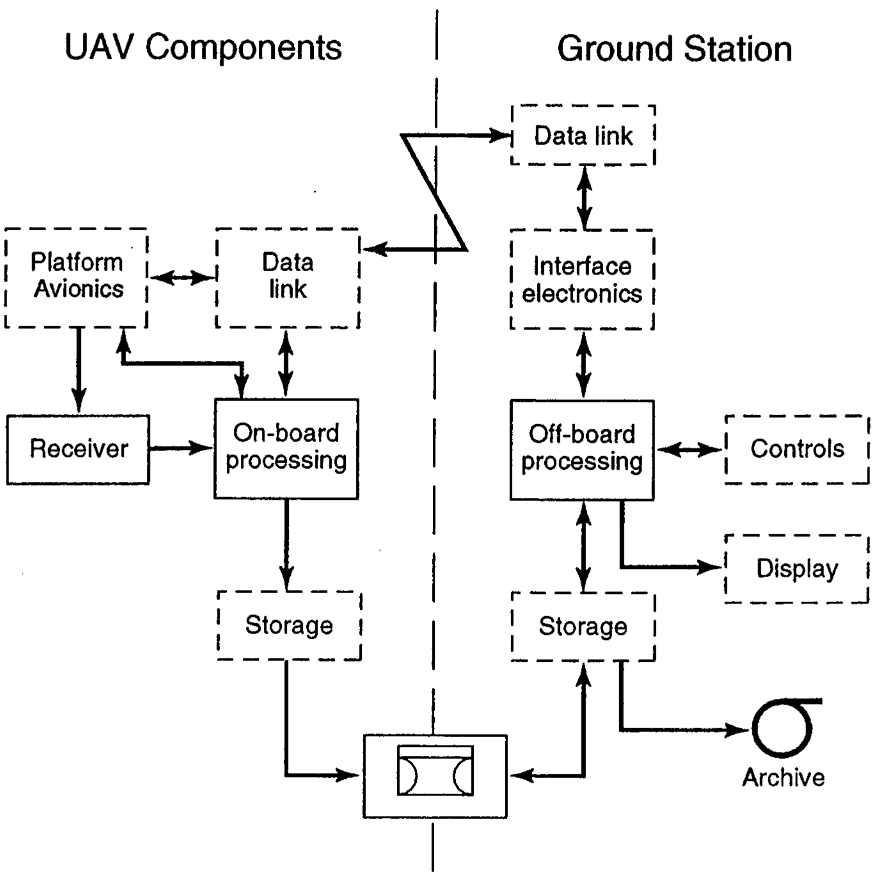

Figure 3. WIS system block diagram.

The WIS is used to generate moderate resolution imagery (1 to 3 mrad) over 100's of spectral bands. The purpose is to use the spectral characteristics of the observed objects to perform the mission. The WIS collects imagery using a "push broom" collection geometry. A typical "push broom" geometry is shown in Fig. 4. Imagery is collected 1 line at a time, across the aircraft's flight path. As the aircraft moves, another line of imagery is collected. The rate at which this imagery is collected is based on the angular size of a single detector element (e.g., the IFOV of a detector element), the sampling of the sensor (typically between 1 to 2 samples per IFOV), the altitude of the air vehicle, and the ground speed of the air vehicle. The WIS uses a unique filter so that 1 line of imagery is collected simultaneously in 100's of spectral bands. The resulting image is often represented as an "image data cube". The dimensions of this "image data cube" are:

(1) Spatial extent along the flight path,
(2) Spatial extent across the flight path,
(3) Spectral content of each pixel.

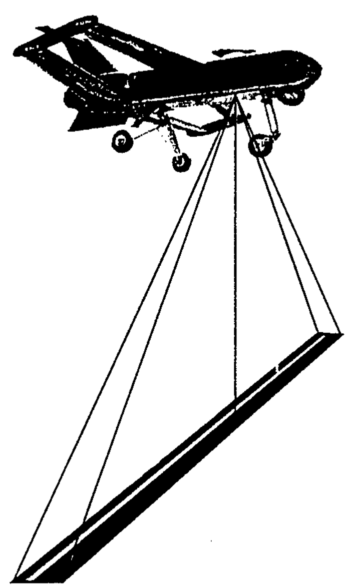

Figure 4. "Push broom" collection geometry for a WIS.

2.1.2 WIS Data Description

For near term application (low speed UAV from a few thousand foot altitude), WIS imagery is collected at a maximum rate of 260 Mbits/sec [640 by 480 (spectral bins) array readout at 60 Hz with a resolution of 14 bits/pixel]. Currently data storage and data link limitations require that the WIS include an on-board processor that will be used to limit the data rate (see Table 1). This data bandwidth reduction is accomplished by reducing the number of spectral bands that are processed. It would be strongly desirable to retain all of this information but this not feasible with the current hardware. The current output data stream is a single serial bit stream. There is the option of providing the data from a single parallel (16 bits wide although only 14 bits contain valid data) data stream. In addition to this imagery data there is annotation data (GPS, INS, etc.) that is included with the imagery data, this results in the need to record an additional 100 kbits/sec data stream. The current data recording capacity requirement is the ability to record 30 to 60 min of data, although this requirement is driven primarily by data recorder technology. From a mission prospective is would be desirable to record up to 240 min of data.

Table 1. Data recorder and data link limit WIS data rate.

Sustained High Speed Data Rate Limitation (Mbits/sec)	Current COTS Hardware for UAV Applications	Currently Available Technology
Digital Data Recorder	32 to 64	107 to 240
Digital Data Link	10	40

The future application of WIS will see an increase in the size of the detector array [1024 by 1024 (spectral bins) instead of 640 by 480 (spectral bins)], improved data resolution (16 bits per pixel instead of 14 bits per pixel) and greatly increased maximum output data rate (400 Hz instead of 60 Hz) in support of finer angular resolution and collection at lower altitudes at a higher speed. This results in a potential future output data rate of up to 6,710 Mbits/sec. This data will probably be provided as raw data over multiple (4 or 8) parallel (16 bits wide) data streams or after some pre-processing in a single parallel (16 bit wide) data stream. In addition to this imagery data there is annotation data (GPS, INS, etc.) that is included with the imagery data, this results in the need to record an additional few 100's kbits/sec data stream.

2.1.3 WIS Physical and Environmental Requirements

Both the current and projected WIS sensor and electronics requires at least 370 W of power, 56 lbs. and 2,800 $in.^3$ of payload capacity and the data link requires at least 1100 W of power, 92 lbs. and 2,600 $in.^3$ of payload capacity. Based on the information about the Tier II UAV (see Fig. 2), the total UAV sensor payload capability is 350 lbs. (including cables) with 1700 W of power available. While based on the information about the TUAV capabilities (see Fig. 1), the total payload volume is 3000 $in.^3$ for primary sensor payload + approx. 5000 $in.^3$ in an external "pod" + 900 $in.^3$ for additional electronics in a common electronics bay. It can be assumed the excess sensor payload capacity could be used for the data recorder (202 lbs., 230 W and 2,300 $in.^3$).

The tactical UAV environment will require operation in a demanding thermal, vibration and shock environment. The typical thermal requirements are:

1) Continuous operation from -54 to +55 °C.
2) Intermittent operation (30 min.) at 71 °C.
3) Storage from -57 to +85 °C.

A typical vibration environment is shown as CURVE IV in Fig. 5. And the sensor should be capable of withstanding 15g, 5.5 msec shocks, along any axis, without damage. The recorder should be capable of operating at altitudes up to 10,000 ft, using only air cooling.

2.2 COMMON APERTURE MULTISPECTRAL SENSOR (CAMS)

2.2.1 CAMS Functional Description

CAMS in an imaging sensor that collects ground imagery from an airborne platform. Typically, this sensor is used to collect reconnaissance or surveillance imagery at low to medium altitudes (from 200 to 50,000 ft). The purpose of CAMS is to upgrade existing AN/AAD-5 film-based infrared linescanning sensors (IRLS) to a 2-color digital capability. The CAMS is used to generate fine resolution imagery (¼ to ½ mrad) over 2 spectral band (LWIR and visible) over a 120° field of view (FOV). The CAMS collects imagery using a "whisk broom" collection geometry. A typical "whisk broom" geometry is shown in Fig. 6. Imagery is collected 1 frame at a time, across the aircraft's flight path. Where each frame consists of 1 to 12 lines of imagery. As the aircraft moves, another frame of imagery is collected. The frames of imagery are collected at a

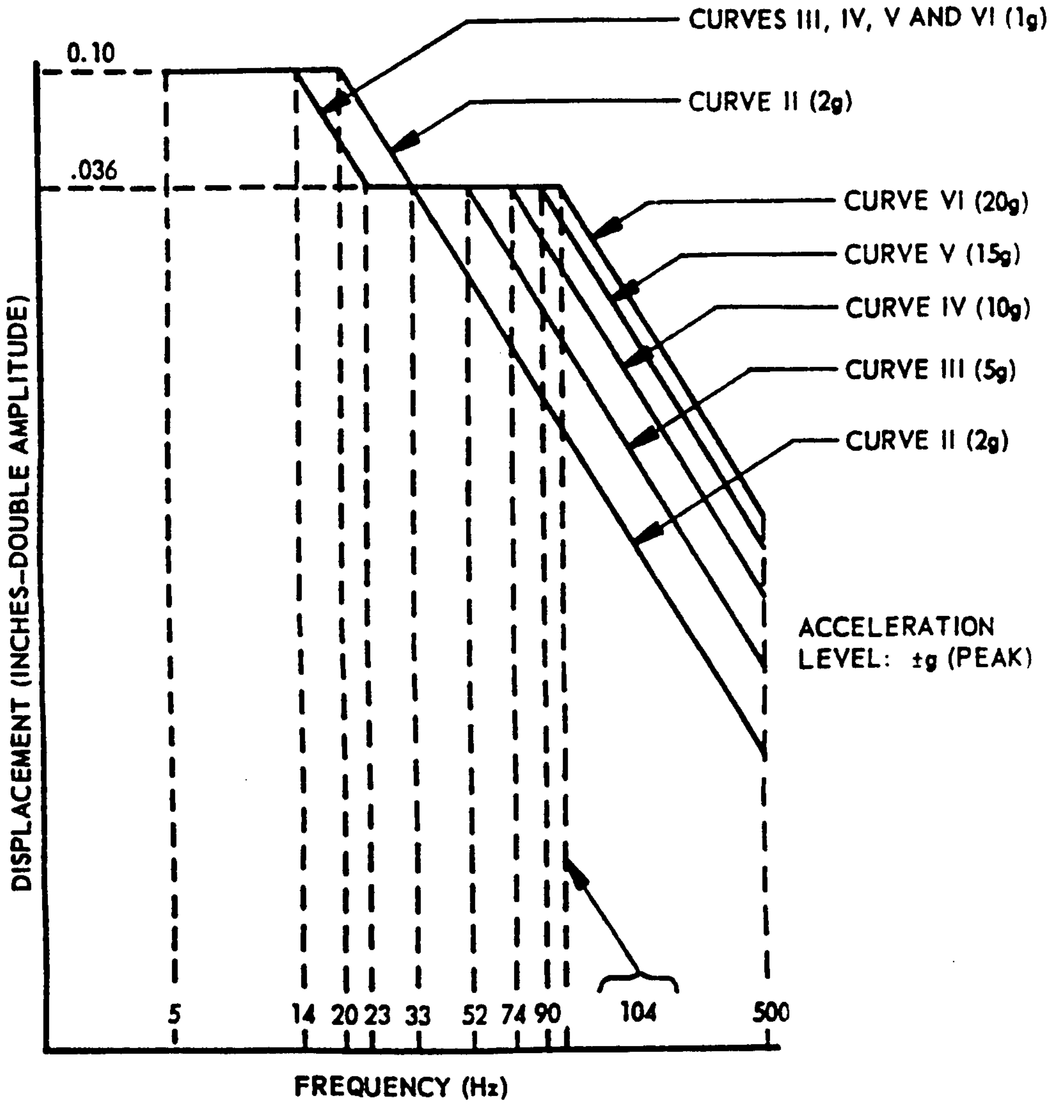

Figure 5. WIS vibration environment.

constant rate (up to 400 Hz in the wide FOV and 200 Hz in the NFOV). The number of lines in each frame (or the height of the frame) is based on the angular size of a single detector element (e.g., the IFOV of a detector element), the altitude of the air vehicle, and the ground speed of the air vehicle.

2.2.2 CAMS Data Description

For near term applications, CAMS imagery is collected at a maximum rate of 107 Mbits/sec. This data rate was driven by the capability of Ampex DCRsi 107 digital

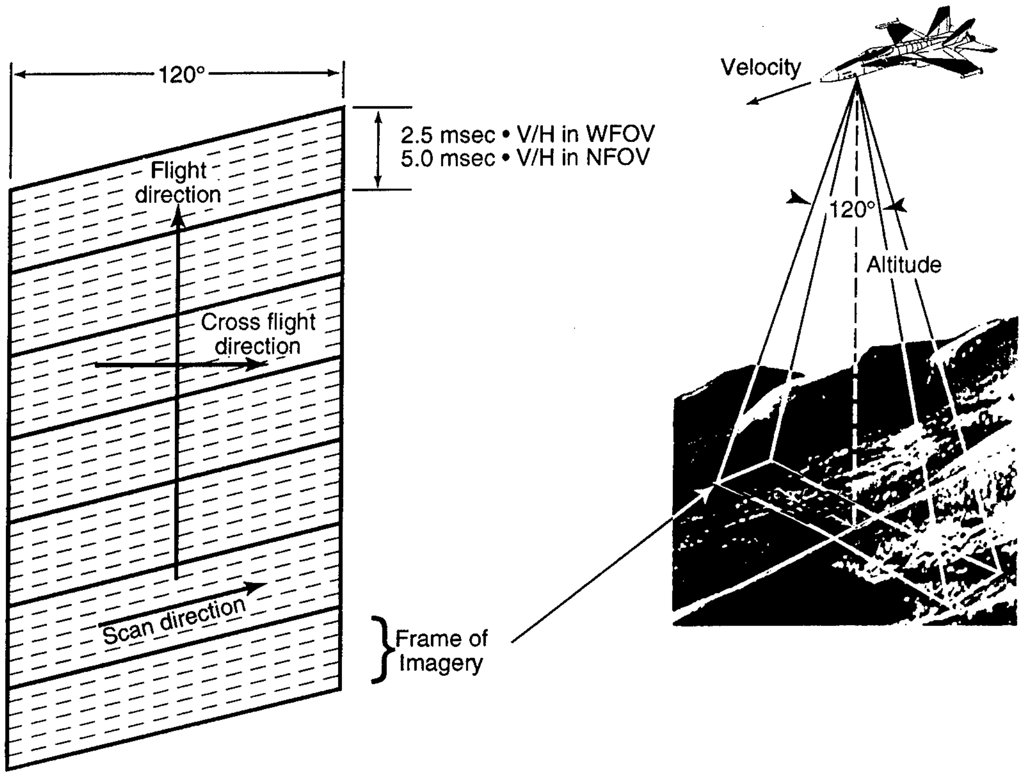

Figure 6. "Whisk broom" collection geometry for the CAMS.

data recorders. Currently, the data recorder maximum data rate requires that the CAMS includes line selection logic [that limits the maximum number of image line to 8 (out of 12)] and that the CAMS uses JPEG data compression. It would be strongly desirable to retain all of this information without the use of compression but this is not feasible with the current data recorder hardware. If all of the CAMS' data were recorded (without compression) the maximum data rate would be 515 Mbits/sec. The current output data stream is a single parallel (8 its wide) data stream. The data capacity is currently driven by the capacity of data recorder of 48 Gbytes, this corresponds to minimum recording capacity (including the effects of compression and line selection logic) of 66 min.

Future application of CAMS might see an increase in the oversampling (from 1.6 to 2.0) and the addition of a third spectral band. This results in a potential future output data rate of up to 970 bits/sec. The data recorder capacity should be at least the current capability (66 min.), although a capacity of 120 min. would be preferred.

2.2.3 CAMS Data Recorder Physical and Environmental Requirements

The near term CAMS data recorder physical requirements would be based on being comparable with the physical requirements of the Ampex DCRsi tape recorder. Specifically, a weight of 77 lbs., a volume of 2,500 in.^{3}, and a power consumption of

250 W. The long term goal, is that the data recorder's physical attributes would be comparable to the current AN/AAD-5 film canister LRU. Specifically, a weight of 30 lbs., a volume of 1,540 $in.^3$, and a power consumption of less than 200 W.

The CAMS environment is even more sever than the WIS environment, specifically an unpressurized portion of a tactical fighter aircraft. This will require operation in a very demanding thermal, vibration and shock environment. The typical thermal requirements are:

(1) Continuous operation from -54 to +55 °C.
(2) Intermittent operation (30 min.) at 71 °C.
(3) Storage from -57 to +85 °C.

The recorder should be capable of operating at altitudes up to 50,000 ft., the altitude/temperature envelope is shown in Fig. 7, CLASS 1 CURVE A. Any cooling is limited to using only air cooling, and should be capable of operating up to 30 min. without cooling air. A typical vibration environment is shown as CURVE IV in Fig. 8. And the sensor should be capable of withstanding 30g, 5.5 msec shocks, along any axis, without damage. The recorder should also operate under 9g acceleration along any axis.

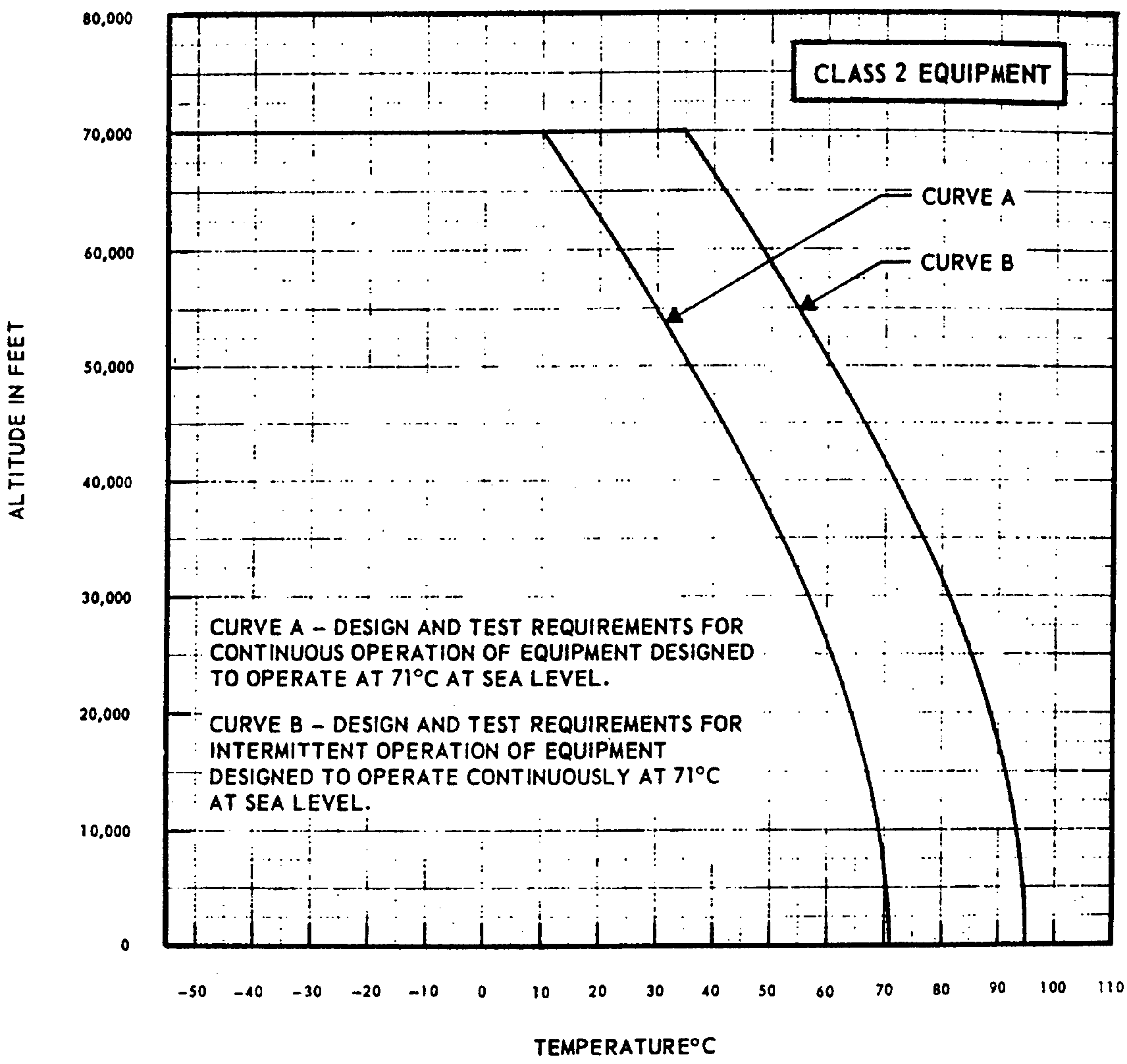

Figure 7. CAMS data recorder vibration environment.

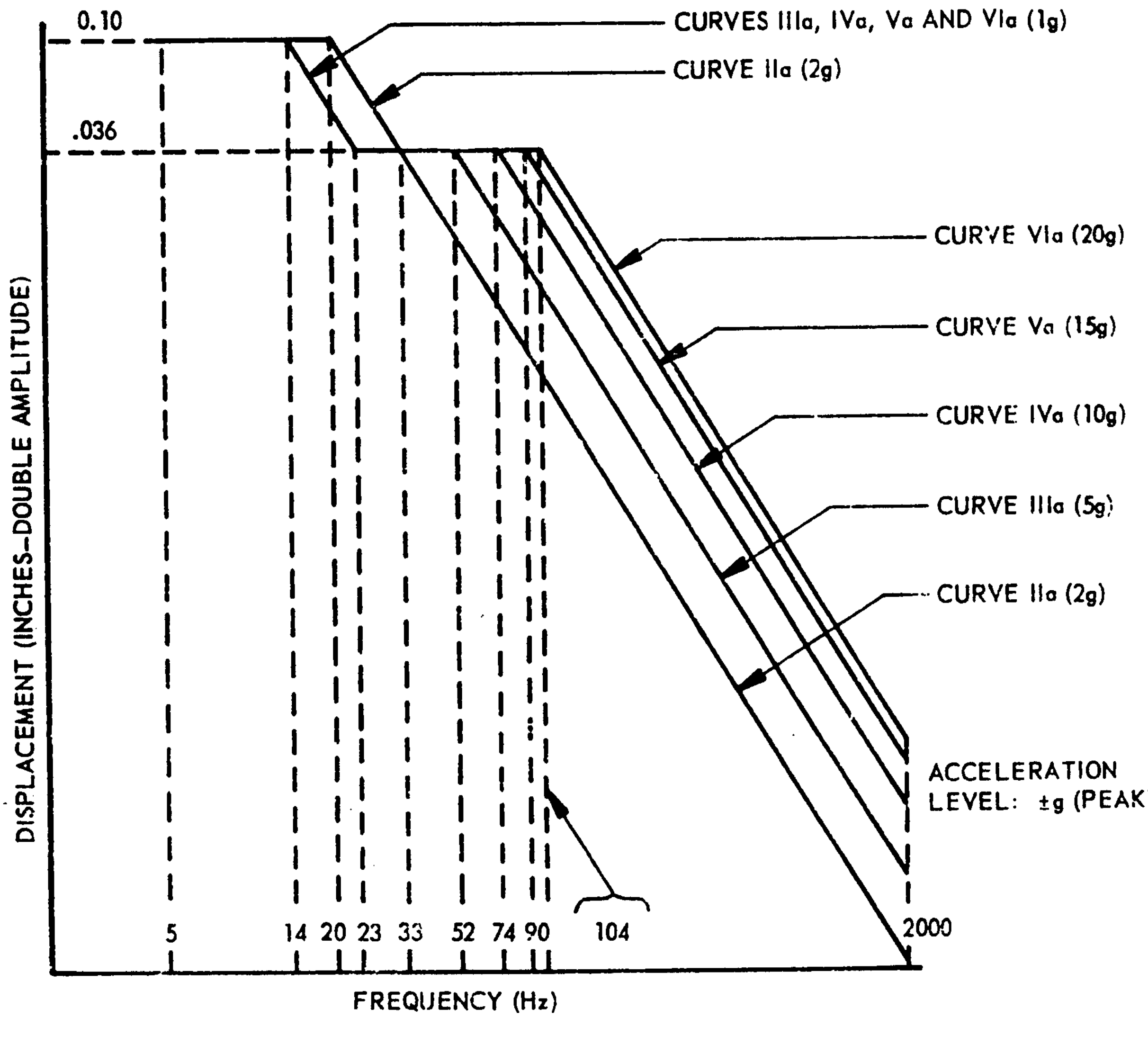

Figure 8. CAMS data recorder temperature/pressure envelope.

Section 3
APPLICABILITY OF 2-PHOTON 3D OPTICAL MEMORY

3.1 CURRENT LIMITATIONS

This section will discuss the limitation associated with the current data recorders (magnetic tape), that could be rectified with 2-photon 3D optical memory technology.

3.1.1 WIS

The current limitation is that the data recorder does not have sufficient throughput to record all of the hyperspectral data. This requires the some pre-processing be performed on the UAV (by selecting only a portion of the available spectral bands). This reduces some of the utility of the WIS, especially for some intelligence missions, i.e., MASINT.

Since this sensor is intended for use on an UAV, the physical limitation (see Sec. 2.1.3) are very constraining. In addition, since the UAV is to be used on a potentially expendable vehicle, their is a strong desire to place the more valuable components of the system (see Fig. 3) in the ground station portion of the system. These constraints aggravates the current limitations, the size and potential expandability discourage the use of a more sophisticated data recorder, while these same constraints makes it desirable to minimize the amount of on-board processing and to perform most of the processing in the off-board processing component of the system.

The integration with a data link gives rise some additional limitations. The planned implementation uses the data link to transmit only a portion of the imagery (few spectral bands) as compare to what is recorded using the on-board data recorder. This is a result of the data recorder having a greater bandwidth than the data link. While it might be possible to playback imagery over the data link, the current data recorder does not allow random access to the data and this limits it playback capability (e.g., time delay in a record-playback-record sequence).

The WIS application also use a RAID hard drive array in the processing of the imagery on the ground. This technology is used so the data can be accessed quickly, both read and write functions are supported and it has sufficient capacity to manipulate hyperspectral image cubes. While the current technology is currently adequate, cost, size and power consumption savings (without sacrificing capacity, throughput or read/write capability) are always desired.

3.1.2 CAMS

The current limitation of traditional tape recorders is that they have insufficient throughput capacity. This requires that CAMS to incorporate data compression and line selection logic to reduce the output data rate. In the future, CAMS will use a smaller recorder, these smaller recorders are currently available (i.e., Metrum 32HE) but they require a greater reliance on data compression and they have less than the desired data storage capacity.

3.2 POTENTIAL ROLE OF 3D 2-PHOTON OPTICAL MEMORY

This section will discuss the potential role of 3D 2-photon optical memory [Refs. 1, 2, 3, 4, 5] to resolve the limitations discussed in Sec. 3.1. In general, the potential data capacity and throughput capacity of 3D 2-photon optical memory [Refs. 3, 4, 5] offers an alternative to the traditional tape recorder technology being used in both the WIS and CAMS systems. It appears that 3D 2-photon memory devices have the potential of alleviating the data throughput imposed limitation associated with both the WIS and the CAMS

3.2.1 WIS

The major role for 3D 2-photon optical memory, for the WIS, is elimination spectral band selection that is currently required based on the bandwidth limitations imposed by the tape recorder. This will allow retention of all of the imagery data collected by WIS. The benefits of retaining all of data include:

(1) More spectral data is available for exploitation,
(2) The frame-to-frame correlation process (that is used to perform electronic stabilization of the image) can now be performed as part of the ground-based post-processing instead of being performed in the UAV on-board processing. Thus reducing size and complexity of the UAV payload.

The ability for 3D 2-photon memory devices to store data in a bulk format (a line or matrix of data at a time) [Refs. 3 and 5] shows a great deal of symmetry to how the data is collected with the WIS. This symmetry could be exploited to simplify the sensor/ recorder interface, e.g., a single frame of data could be recorded on a single plane in the memory device, and further simplify the on-board processing requirements.

The other major potential benefit of this technology, for a WIS application, is to reduce the size of the data recorder unit. The memory media appears to have the benefit of a very high memory density [Refs. 1, 3, and 5] and the ability to support vector parallel and image parallel [Refs. 3 and 5] data storage. This implies that there is the potential that a memory storage device based on 3-D 2-photon memory could be more compact as compared to a traditional high capacity digital tape recorder.

3.2.2 CAMS

The major role for 3D 2-photon optical memory, for the CAMS, is elimination data compression and simplification of the line selection logic that is currently required based on the bandwidth limitations imposed by the tape recorder. The elimination of compression will eliminate the losses in fidelity associated with JPEG compression and simplify the image playback process (simplifying the ground station). The simplification of the line selection logic with alleviate the undersampling of the image, in the flight path direction (see Fig. 6), that occurs during low altitude/high velocity image collection. In addition, the increased bandwidth capacity of 3D 2-photon memory devices [Refs. 3, 4 and 5] will allow increasing the image sampling in the cross flight direction. Currently, CAMS samples at 1.6 samples per IFOV which is less than preferred sampling rate of 2 samples per IFOV (based on Nyquist criteria). By increasing the sampling frequency, the ability of CAMS to resolve low intensity object at high spatial frequencies will improve.

Section 4
2-PHOTON 3D OPTICAL MEMORY DEVELOPMENT RECOMMENDATIONS

4.1 STORAGE DEVICE RECOMMENDATIONS

A storage device is more than just the storage media. The packing of optical memory into a mass storage device needs additional development. The first step would be for a storage devices that has similar interface to exiting data recorders (e.g., ECL data interface, serial/parallel data interface) but provides a significant enhancement (e.g., 1 Gbit/sec throughput rate, multiple separate high speed data ports, or 10 Tbit capacity) over existing data recorders. For this to be viable alternatives to tape recorders, the memory device should have a footprint that is comparable (in not smaller) than current generation tape recorders.

Some design work needs to be performed to demonstrate that 2-photon 3D optical memory technology is compatible with operating in a tactical airborne environment (especially temperature ranges and vibration). Specifically, what type of alignments and stabilization will be required to maintain the high data density [Refs. 1, 3 and 5] and is this practical in a tactical airborne environment.

A final concern is the scaling of this technology to a large capacity storage device. Some risk reduction will need to be performed to validate that scaling this technology will not limit its performance. For example, will the information and addressing beams [Ref. 3] suffer significant degradation if they are interrogating [reading or writing] a site in the middle of a large specimen (in other words, will 100's Gbytes of previously written data near the outer surfaces of the optical memory interfere with the writing/reading to a location in the middle of the device if the addressing and information beams must first pass though this previously utilized volume).

4.2 OTHER POTENTIAL APPLICATION

In addition to the applications addressed in the report there are some addition potential applications for this technology. This include storage of synthetic aperture raiders (SAR) data, and processing multidimensional (3-4) sensor data. SAR sensors typically output a large quantity of data, include phase information in addition spatial and

temporal information and have data throughput limitation and storage requirements comparable to hyperspectral sensors.

In addition to data storage there might also be a way to use 3D optical memory to perform some image processing functions. Specifically, for SAR or hyperspectral image processing, by writing the data in along certain axes and then read out the data from another direction.

REFERENCES

1. Esener, S., and P. M. Rentzepis, "Two-photon 3-D Optical Memories," SPIE, Vol. 1499, 1991,, pp. 144-147.

2. Dvornikov, A. S. and P. M. Rentzepis, "Studies on 3D Volume Memory," SPIE, Vol. 1662, 1992, pp. 197-204.

3. Esener, S., et al., "Two Photon Three Dimensional Memory Hierarchy," SPIE Vol. 1773, 1992, pp. 346-355.

4. Bai, Y. S., A. Shen, and R. Kachru, "Frequency and Time Domain Hybrid Optical Memory," SPIE Vol. 1773, 1992, pp. 356-357.

5. Jamberdino, A. A., F. N. Haritatos, and B. W. Canfield, *Optical Memories for Large Data Base Applications*, Rome Laboratory, Griffiss AFB, NY.

APPENDIX C -
RAYTHEON–E-SYSTEMS REPORT

13 October 1997

STUDY REPORT

APPLICABILITY OF 2-PHOTON 3-D OPTICAL MEMORY TECHNOLOGY

1. INTRODUCTION

The study of two photon 3-D Optical Memory Technology was undertaken to determine the applicability of this technology to Tactical Imagery Programs such as Joint Service Imagery Processing Systems (JSIPS) and related imagery processing programs.

2. DOCUMENTS REVIEWED

The following documents were furnished by Synectics Corporation and used in reviewing the 2-Photon 3-D Optical Memory Technology:

Sadik Esener and P. M. Rentzepis, "Two-photon 3-D optical memories", SPIE Vol. 1499, pp. 144-147 (1992)

A. S. Dvornikov and P. M. Rentzepis, "Studies on 3D Volume Memory", SPIE Vol. 1662, pp. 197-204 (1992)

S. Esener, Y. Fainman, J. Ford and S; Hunter, "Two Photon Three Dimensional Memory Hierarchy", SPIE Vol. 1773, pp. 346-357 (1992)

A. A. Jamberdino, F. N. Haritos and Capt. B. W. Canfield, "Optical Memories for Large Data Base Applications", Paper from Rome Laboratory

F. N. Haritos, "3-D Optical Memory Development Schedule", Paper from Rome Laboratory

3. APPLICABLE SYSTEMS

3.1 JSIPS and Related Tactical Processing Systems

JSIPS has become a series of programs for building new systems, updating existing systems, and on-going support for existing systems. In addition, the processing and display functions that were part of JSIPS are evolving and being further developed for use in other tactical systems. Many of these systems share the memory requirements with the basic JSIPS. Therefore, the determination of the utility of this type of optical memory will consider all of the related tactical systems as well as JSIPS.

3.2 Common Image Processor (CIP) Related Systems

The Risk Reduction Image Processor (RRIP) is being developed under contract to ESC at the present time. It will have the capabilities to accept, process and output imagery of multiple types, from multiple platforms at varying downlink rates. For some of the processing requirements, the memory that would be useful is larger than what is usable today within the size constraints. The utility of this subject type of optical memory will be discussed as a candidate for the RRIP and related functional systems.

4. ANALYSIS OF MEMORY USAGE WITHIN THE APPLICABLE SYSTEMS

4.1 Method of Analysis

The memory usage within the applicable systems presented in section 3.0 above, will be analyzed with respect to multiple parameters. Some of these parameters are memory capacity, the input data rate required for downlink support or other input support, the output data rate required to meet timelines or other requirements, the requirements, if any, for retention of data (and conversely the requirements for deletion of data), power requirements, cooling required (particularly cooling below normal air conditioning temperatures), size constraints, and any environmental factors that impact the current or future storage methods.

While there is no intention to provide a detailed analysis of these systems, a presentation of the present parameters and/or a projection of the future requirements will be given.

4.2 Present Mass Storage Methods

4.2.1 Current Operational Mass Storage Requirements in Applicable Systems

4.2.1.1 Current operational mass storage requirements for JSIPS related systems.

The Tactical Input processing function for the JSIPS related systems utilizes the majority of the mass storage. The present systems utilize high-speed digital tape recorders to provide this storage. The current design utilizes three ID-1 type recorders to record and reproduce data for distribution through the processing path. Two recorders are used as the capture/reproduce recorders for the input data. The third recorder provides an archive function for the processed data.

Each large tape cassette has the capability to hold approximately 95 gigabytes of data. Since the input imagery has multiple types of sensors, multiple array sizes for the sensors, and multiple modes of operation, the number of images that the cassette holds is impossible to state with any degree of accuracy. However, this capacity does represent approximately 50 minutes of data input at the 274 Mb/s downlink rate. Thus for longer mission recordings, the two capture recorders have to be multiplexed to ensure recording of the downlink data.

4.2.1.2 Current operational mass storage requirements for CIP related systems.

There is only one requirement for mass storage in the CIP related systems today. This requirement is for the processing of the input data. No precessed imagery is maintained within the CIP and related systems. The storage needs are generally driven by the processing of the radar data, rather than any of the other types of data. To some extent, the algorithms used for the radar processing are determined by the speed and availability of the computers used and of the mass storage used. With the advent of larger random storage capabilities and utilizing the faster computing capabilities, the processing algorithm could very well change to increase the information content available for display.

In general, the requirements cited above in the JSIPS section also apply to the CIP related systems. The difference is that at the present time the CIP is a processing element only, and the input and output storage necessary to accomplish the mission is the responsibility of the using function.

4.2.2 Current Operational Mass Storage Deficiencies in Applicable Systems

4.2.2.1 Current operational mass storage deficiencies for JSIPS related systems.

There are no deficiencies in the present systems since the systems meet the requirements for delivery to the customers. However, there are areas in the specifications that could be changed if a different storage system were available. Also, operational requirements could be changed if a different storage system were available.

The use of the higher rate downlink is presently very limited because recorders that will operate at sufficient data rates to record the data from a 548 Mb/s downlink are just becoming available as true operational units. In addition, these higher data rate recorder have a higher initial cost, and are expected to have higher maintenance costs through the useful lifetime. In addition, with the usage of the same tape cassettes, the available recording time is halved to approximately 25 minutes. Thus more emphasis will be placed on the multiplexing of recorders for raw data recording. Furthermore, in order to have timely exploitation and archive recording of the data, additional recorders may be required for the archive function, thus further increasing the system costs.

The need for multiplexing and for changing of tapes for both capture and archive of data forces the need for full time personnel to operate the tape recorders. In addition, there is a need for a relatively large store of tape cassettes to service the capture function. The may be no time available during a long capture to erase tapes that have completed the reproduction cycle.

4.2.2.2 Current operational mass storage deficiencies for CIP related systems.

As stated above in paragraph 4.2.1.2, the mass storage could be a factor in the capability for radar processing. In addition, there is an economy of scale in having the memory associated with the CIP function rather than as part of the using system. The availability of large mass storage systems will hasten the recognition of this economy and enhance the system to be delivered.

4.2.3 Projected Future Mass Storage Requirements in Applicable Systems

The need for larger amounts of mass storage in all types of systems will continue to rise. There is no limit to the capability of the applicable systems (and multiple others) to utilize mass storage. With additional on-line storage available, the archiving tasks, particularly the short term archives, have less utility or no utility at all.

The capability of the systems will be, to some extent, driven by the availability of larger and more cost effective mass storage systems. With the continuing reduction of military budgets, costs (both initial and operational) will be a large factor in the types and numbers of systems used.

The trend, for downlinking image data, is to downlink for long periods of time. Some UAV's, for instance, can and do stay on station for multiple hours with data continuously downlinked. To have a quick method to select and view portions of the data available, the display station must have large amounts of quickly accessible memory. The needed capability is not presently available using the semiconductor memory technology. To achieve these capabilities, a new methodology must be found. The two photon 3-D optical memory may fill this need.

4.3 Two Photon 3-D Optical Memory Methods

The two photon 3-D optical memory appears to have many desirable qualities to address both the present problems in existing system designs and the future requirements for storage. At the present time no other memory with this potential appears to be in work.

4.4 Transition of the 2-photon 3-D Optical Memory from the Laboratory to the Operational Environment

Several considerations will be discussed in determining what must take place to transition the 2-photon 3-D Optical Memory from the present (laboratory demonstration model) to an operational environment to include field usage. The first topic would be to develop materials that will operate at room temperatures. The material provided for this review indicates that some of the materials need to be operated at cold temperatures while others can be used at room temperatures. While the initial work seems to have been done with the cold-requiring materials, this is a detriment to both commercial and military usage. Particularly, military operations in the field would class the need for temperatures lower than those provided by normal air conditioning as an undesirable requirement and would probably greatly reduce the usage of the memory.

A second consideration is the speed of operation. While it is of great interest to store large amounts of data in a small space, the rate of writing the data and the rate of retrieval of the data are also of great interest. With computer speed continually increasing and the reliance of military systems on the use of computers, the data rates of the memory must be maximized. If individual data

groupings can not be written to, and from read at data rates up to at least 100 megabytes, then a method of paralleling the memories must be accomplished. If this proves to be too costly or increases the size too much, the memory may not be acceptable. The paralleling process could be a likened to a disc raid system, in that, both increased speed and error protection could be accommodated.

A third item, though not discussed in the literature, is a concern that the size of each memory cell may require extreme stability in mounting of the memory material and the laser equipment. If there is a need for optical bench mounting or other such movement prevention devices, the desirability of the memory will be diminished.

The majority of the paragraphs previously discussed are in the context of military systems and the usage by these systems. However, the military of today is relying more and more on commercial off-the-shelf equipment and software to accomplish the required missions. For this reason, one of the transition topics would be to move this memory into the commercial arena once the development has been completed. By licensing (or some other means of transfer) the technology to commercial companies, a diverse usage would be encouraged. With the increased usage, and the manufacturing inovations of the commercial companies, the production costs would drop quickly. In particular, if the memory technology were available to computer manufacturers, the spread to many of the military applications would be eased.

5. CONCLUSIONS

The two-photon, 3-D Optical Memory has a large potential in both military systems and commercial systems, if the transition to the operational environment can be accomplished with no loss of capability. If the transition can not be completed (lower temperatures required, extremely high stability mountings required, etc.) then this memory will have only limited usefulness and it will not be fully accepted by either the military or the commercial world.

APPENDIX D -
RISING EDGE TECHNOLOGIES, INC. REPORT

Rising Edge Technologies

F9008
3 March 1998

3-D Optical Cube Memory in Commercial Storage Environments

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Introduction

The demand for high capacity storage systems grows exponentially as digital data becomes a more integrated part of the everyday functions of society. Imaging, or converting physical items such as paper or film to a digital format, continues to become more commonplace. Table 1 illustrates some common examples of the file size demands different imaging applications place on storage systems.

Table 1. An Overview of Common Data File Sizes.

Image Description	File Size (Bytes)
One Picture (JPEG)	80 kB
One Page Document (TIFF)	80 kB
One Picture (GIF)	200 kB
One MR 512x512 slice	500 kB
One MR 1kx1k slice	2 MB
10'x12' x-ray (300 dpi, 8 bit)	10 MB
14"x17" x-ray (300 dpi, 12 bit)	42 MB
One MR 512x512x128 slice (16 bit)	64 MB
One Mammogram	150 MB
One MR 1kx1kx128 slice (16 bit)	250 MB
Large Satellite Image	1 GB

The data storage market is characterized by a number of products, generically classified as fixed and removable storage devices. Fixed storage is dominated by the magnetic hard disk drive. With capacities climbing and prices dropping, it is the most common, and popular, storage technology in use today. The removable storage category includes a multitude of devices including floppy disk drives, cartridge hard drives, optical storage devices (magneto-optical, phase change, CD-ROM, DVD), and tape. Storage sub-systems designed to play on the strengths of these devices offer another class of storage products to consider.

In establishing a basis for comparison between the 3-D Optical Cube Memory and other storage alternatives, it is the storage sub-systems market that must be reviewed. Figure 1 illustrates the wide range of capacity and performance alternatives available from the storage marketplace. There are several characteristics of storage systems that tend to get lost as one moves away from component storage and towards sub-systems. Namely, access time and size tend to increase.

As multiple storage devices are assembled in a system, access time becomes the cumulative effect of the host system performance, application software, and hardware characteristics. Of these, hardware characteristics are the easiest to quantify. In multiple device systems, the characteristics of the storage device (i.e. random access, sequential access, media type, interface performance, etc.) may have the smallest impact on access time. If the system supports media exchange,

robotics can have the greatest impact on access time. Additionally, the incremental growth in physical size of the system as capacity increases can become a major factor in facilities planning and support issues.

3-D Optical Cube Memory addresses several of these often ignored factors thus making it an extremely attractive candidate in the storage sub-system market. This paper will review several potential markets for this technology and evaluate the potential of 3-D Optical Cube Memory as a viable storage technology device in these markets.

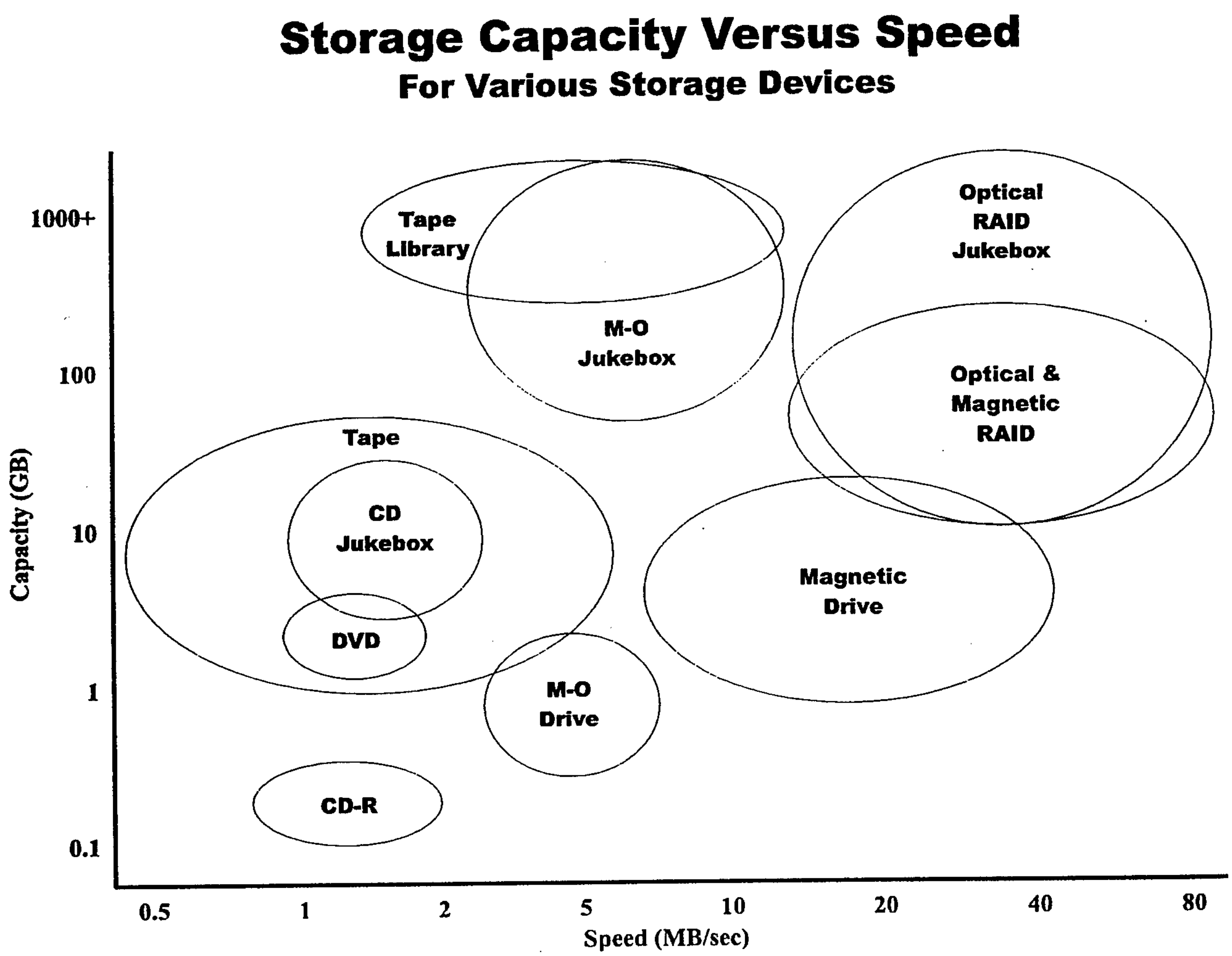

Figure 1. Comparison of Storage Devices for Speed and Capacity

Industries

Document Imaging Market

Document imaging systems can range in size and complexity and be designed to support capture, interchange, retrieval, or archive. The Electronic Document Capture (EDC) industry is growing rapidly based on a wealth of products and solutions. As a whole, the EDC market stood at $600 million in 1996 with growth expected to exceed 50% annually for the foreseeable future. Generically defined, EDC systems create images of paper documents through scanning. Among document storage options, COLD remains a hot technology. COLD, or Computer Output to Laser Disk, is a means of recording electronic documents as images for storage and retrieval. COLD systems capture the document images and create copies of computer-generated documents exactly as they would appear in printed form.

To some in the industry, "COLD" is a misnomer, as the market has grown beyond document storage and retrieval. Today, COLD systems are moving toward integration with document imaging systems and are being used in conjunction with workflow, data warehousing and data mining tools. Newer systems support cross-platform functionality and systems that use industry standards for databases, indexing and compression.

Market trends show vendors moving away from proprietary systems and towards cross-platform support with Internet/intranet browser capabilities. Browser-enabled systems however, are unlikely to be "production ready" until 1998. Other trends show COLD converging with report distribution systems and the Computer Output to Microfiche/Replacement market into a broad category named DARS, for Document Archival and Retrieval Systems. Some analysts place the value of the North American DARS market at $600 million in 1996, with compounded growth rates of 30 percent projected through 2001.

Today, more than 300 vendors fall into the DARS market category. Business analysts project only 20 to 25 of these existing vendors will survive the impending consolidation. This convergence is expected to occur as the requirements for competing in the marketplace, as well as the product requirements, become more complex. Only companies with large revenue bases will be able to effectively compete.

By the end of 1995, 15,000 COLD systems had been installed worldwide, with an estimated market value of $325 million. Growth projections put the market at $454 million in 1996 with an annual growth rate of about 60 percent. Analyst also indicate this growth may be fueled by the potential for significant returns on investment in as little as 12 months.

One example cited relates to the investment service Charles Schwab. Schwab had been spending $40,000 a month on microfiche to store about 15 million pages. By installing its $1 million COLD system, the investment service not only eliminated microfiche costs; it also improved productivity and cut labor needs for some customer service functions in half. Where it once could take minutes to retrieve a document stored on microfiche, employees could call up a document on his or her desktop PC in seconds. Furthermore, a customer service worker can retrieve an exact replica of the document that was sent to a client, making it easier to answer customer queries. Employees can even send duplicate documents to customers via fax from their desktops.

COLD systems can cost anywhere from about $50,000 to several million dollars, depending on size and volume. A basic system will include software for recording, indexing and retrieving documents; a server; and a storage mechanism, such as CD-ROMs or RAID (Redundant Array of Independent Disks). Proponents of COLD systems site no real disadvantages to these systems. However, achieving a performance balance in the user environment remains the greatest challenge. Many companies focus solely on capture and ignore retrieval. Thus, systems often end up not meeting the demands of the users in terms of document retrieval and indexing.

Driving Storage Requirements

COLD is not a new technology. Niche vendors introduced COLD systems about a decade ago as a way for companies to replace paper or microfiche for document storage. Early adopters, naturally enough, were institutions that produce reams of paperwork, such as health care and financial services. But COLD has garnered increased attention in the past few years, as more companies recognize the potential for savings and as larger vendors (IBM, Wang, Kodak and FileNet among them) see the value of being in the marketplace.

The Medical Imaging Market

Information Technology (IT) in the health care market is expected to grow rapidly as consolidation in the industry forces IT planners to revisit existing systems as well as install new equipment. Analysts predict a 35% growth in IT spending during fiscal 1997. In fact, the health care information technology sector could hit $21 billion by the year 2000. A compounded annual growth rate of 15%. A 1996 survey of 1200 health care and technology professionals by the Healthcare Information and Management Systems Society, Chicago, found that two-thirds of the participants expected to increase spending on information technology by 20% in the next two years. The remaining 25% of survey respondents expected spending to increase 50% over the next two years.

The growth in this industry can be attributed to a fundamental desire to reduce cost and improve customer service. These improvements are expected to be made by targeting infrastructure applications such as data repositories, interface engines, master patient indices and work-flow management applications, computerized patient records, physician workstations, managed care systems, and decision support applications.

A typical IT infrastructure in the medical industry parallels that of many other industries; legacy systems being driven aggressively towards client/server architecture. At the core of this growth is the need to integrate hardware, applications and data. At a minimum, the industry is looking for better patient indexing and record keeping (all patient information in a common place) as well as resource scheduling. As this trend continues, it is expected that within the next five years, all health care institutions will have a data warehouse system in place.

Despite the demand for products and services in this market sector, a clear leader has yet to emerge. From a storage perspective, the trend in systems is towards capacity and archive. Other factors to be considered include reliability and redundancy, as well as performance from both the hardware and software components connected to the system.

Driving Storage Requirements

An increasing number of hospitals, laboratories, doctors, and medical research centers are relying on digital imaging to help speed diagnosis, save money, improve treatment quality, and accelerate medical training. Images from diagnostic tools such as CAT scanners, MRI, echocardiograms, and X-rays are increasingly being stored digitally and used either locally or in remote locations.

A single 30-second echocardiogram, for instance, can take up to 10 GB of disk or tape storage. A major medical center running multiple radiology rooms can easily generate over two Terabytes of images each year. As the use of 3-D images, animation, and digital video increases, the need for high capacity, high speed data storage will grow with it. Some of the key requirements in medical imaging backup include long media life, cost-effective performance, rapid data transfer and ease of media interchange to support high capacity.

In the consolidated healthcare market, the data warehouse and datamart become driving forces in decision support systems. The data warehouse touches on a major shift in business practice; that better information provides the only true competitive advantage. In a high-tech economy, the traditional cornerstones of competition (land, labor, capital) take on less importance. But better information or, more specifically, the ability to better access and analyze strategic information stands out as an asset that is difficult for competitors to duplicate. Data warehouse implementations are typically suited to multi-Terabyte information support needs.

As more healthcare providers and suppliers adopt data warehousing and similar practices to make better use of their patient information, those slow to make the move become more vulnerable. The recognition of this fact is easily supported by the growth projections for IT support in this industry. A data warehouse can be a powerful tool, for organizing mountains of patient information. But a poorly built data warehouse will fail to live up to its promise. As the healthcare industry moves toward data warehousing, they will look to accomplish the following functions:

- The data warehouse must be an enterprise solution.
- The data must be complete, accurate, and consistently defined.
- The project must use the minimal set of technology components.
- Data must be managed at the detail level.
- An information directory must be available to all knowledge workers.
- Definitions established for the data warehouse must carry over into operational data.

The datamart, sometimes referred to as datamall, offers a low cost, short turnaround solution to the benefits of strategic decision making. As more and more data is collected, compiled, and analyzed, datamarts offer healthcare providers a better way to access and utilize the resulting information. Typically, datamarts are designed to meet the specific needs of specialized departments within an organization whose information storage requirements total 100 Gigabytes or less.

Datamarts have emerged as a viable alternative to data warehousing systems. They are essentially scaled-down versions of the data warehouse. One of the primary reasons datamarts are gaining in popularity over data warehouse projects is their scale. In a data warehouse, information from

different departments is pulled together in one monolithic system that may end up costing too much, taking too long to deliver, and usually not meet the requirements or expectations of its end users. The datamart offers a much more controlled growth path without the monolithic scale of a data warehouse. Datamarts are often later tied together to form a distributed data warehouse.

Some of the key implementation issues in datamart systems include low cost, ease of use, host platform independence, and the ability of the system to seamlessly support the work environment where the system will be installed. A well designed datamart can help a business organization offer better customer service; create greater customer loyalty and activity; focus selling, service, and support efforts for large and small customers; increase revenues; and reduce operating costs.

There is also a growing undercurrent in support of the computer-based patient record. A computer-based patient record (CPR) is electronically maintained information about an individual's lifetime health status and health care history. CPRs are not merely automated forms of today's paper-based medical records, but encompass the entire scope of health information in all media forms. Thus CPRs include medical history, current medications, laboratory test results, x-ray images, and so on.

Proponents of CPR generically think of record storage in terms of the physical location of data, not the storage support system. In computer-based patient record systems, health data are distributed across multiple systems at different sites. Because of this, there needs to be common access protocols, retention schedules, and universal identification. There are numerous standards and organizing committees working to define protocols for the CPR. This will hopefully result in a well defined system designed to facilitate the capture, storage, processing, communication, security, and presentation of non-redundant health information.

The ultimate CPR system would operate not as a massive database, but independent computer systems at individual care sites with minimum connectivity requirements and appropriate security so that specific data can be accessed from any system upon authorization of the patient. CPR systems provide availability to complete and accurate patient data, clinical reminders and alerts, decision support, and links to bodies of related data and knowledge bases. The ideal CPR system can warn a caregiver when there is an allergy to a medication being prescribed, provide the latest research on treatment modalities, and organize volumes of information about a patient's chronic condition.

Computerization of health information offers many opportunities to improve the nation's health care and reduce its costs. A solid foundation of information used during the care process and as a source of scientific data on which to base rational health care policies is critical to improving health care quality, reducing cost, and assuring access to care. Such a foundation of health information cannot be accomplished through simply automating the existing paper medical record or creating massive databases. A fundamental change in information gathering, use, and access is necessary.

Alternative Markets: Media Content Developers

The basic market characteristics examined for document imaging and medical systems can be applied to other vertical markets. Consider the media development market and the growing

popularity of nonlinear digital editing. The nonlinear editing market has always been somewhat of a roller coaster, suffering from what industry insiders call "video recessions". Despite the fact that nonlinear editing suites are generally faster, easier to use, and equipped with more features than tape-based systems, only 20 percent of the editing workstations in use today are nonlinear.

Reasons cited for this slow adoption of the technology include the market shake up of Apple computers. As recently as 1995, nonlinear video editing was almost entirely a Mac market. Questions about the shrinking of the Mac market and the growth of Windows market had many people wondering. Naturally, video houses delayed upgrading their analog editing systems until they had decided which operating system they were going to support. Today, customers are more comfortable about the move to Windows as more high quality systems enter the market. Current estimates show that the nonlinear editing market is growing at a rate of 20 percent annually.

The emergence of Windows in this market has been driven by some unlikely factors. The arrival of digital editing in the corporate environment for projects like promotional videos has changed purchasing dynamics in favor of NT. This shift in the purchase decision cycle from the creative people (traditionally Mac enthusiasts) to IS people (usually implementing corporate wide NT solutions) has helped bolster sales for NT based platforms. However, in terms of the professional editor supporting broadcast quality video, Mac platforms still dominate.

Another factor contributing to the growth of nonlinear editing is the falling price of disk drives. In the past, to remain affordable despite high disk drive prices, nonlinear editing systems typically incorporated compression techniques that reduced resolution. Now users get more storage for their editing dollars, and systems rely less on compression.

Driving Storage Requirements

There are three areas associated with nonlinear editing and media content development that are driving storage vendors to re-evaluate their technology to meet the needs of professional content developers.

Film Editing

Traditional film editing left a large portion of the footage shot on the cutting room floor. Linear editing techniques forced film editors to review film footage and manually cut and splice together desirable sections to create the final version of the film they wanted. Digital editing systems combine RAM and high capacity disk drives to allow editors to interactively edit and manipulate digital images in order to create a final product. These systems are very effective for supporting the project at hand. However, they also require a backup system, usually tape, to store completed work and works in progress.

With the growing emphasis on digital effects and computer generated images in the film industry, the demand for storage systems is expected to grow dramatically. Each frame of film requires about 40 Megabytes of disk storage. Since film runs at 24 frames per second, it doesn't take long for the storage requirements of a typical project to run into many Gigabytes. Furthermore, many special effects projects are created by superimposing several layers of digital images, effectively multiplying the amount of data involved in the average project into hundreds of Gigabytes.

Video Editing

Unlike a film editing, video editing applications usually find the editor working on several projects at once. In this scenario, it is not unlikely for each project to require multi-Gigabytes of storage. The dynamics of such an environment force the editor into a routine of performing continuos backups. A video editor may work on one project to complete a scene or edit existing footage only to be bumped to something with a higher priority or closer deadline. In this digital environment, the project is usually so large that it is only possible to work on one at a time. This forces the editor to rely on off-load/back-up systems to remove the project from the system hard disk so work on the next project can begin.

Multimedia

Multimedia developers blend many different elements into one unified presentation or product. It is not uncommon for today's multimedia files to blend live action, graphics, music, sound effects, photographs, dialogue, and other elements into a single product. Each element is key to the developers vision in telling a story, engaging the viewer, or conveying a message. The level of effort to create such a program can easily take a year or more. Speed and reliability become critical factors in ensuring no time is lost due to limitations imposed by the development tools.

Television-quality animation usually demands 1 MB of data per frame. As with film and video, animation runs at 24 frames per second. Thus, a 30 second commercial would require a minimum of 720 MB of storage. As complexity goes up, so do the storage requirements. If an animator works on more than one project at a time, again the storage demands increase.

Other Factors

Storage system performance is also a critical factor in content creation. The longer it takes to produce or render an image or segment, the fewer projects that can be performed that day. Thus, speed and archive (the ability to free system storage space for additional projects) are critical to generating revenue for the content developer. From another perspective, if performance and capacity were sufficient, it may be possible to leave media material on the system and reduce the near term demand for archive on a daily basis.

Available Storage Devices

To fulfill the needs of these industries, there exist a multitude of storage apparatus representing a wide spectrum of capabilities. Each device or sub-system has its own strengths and weaknesses making it suitable for some applications while undesirable for others. In this section, we will attempt to quantify attributes of each device with respect to performance, cost, and physical characteristic and then, analyze which devices are best suited for these markets. First, a brief overview of the candidate storage technologies is presented.

CD-R Drive - Recordable Compact Disk drives use the familiar CD as removable WORM (e.g. cannot erase data once it is written) media. Although their wide

availability and standardization have made them popular, their slow transfer rates and small capacity limit their usefulness.

M-O Drive - Magneto-optical drives offer an improvement in both capacity and throughput over CD-R with the added benefit of rewritability (erasability). A major drawback is that these 5¼" cartridges are double-sided, thus they must be physically flipped to access the full capacity. They remain somewhat of a niche product and have yet to realize their full market potential.

Tape Drive - Although tapes offer the lowest cost media, the sequential access severely limits access time and makes tape drives unusable for many applications.

Magnetic Drive - The ubiquitous hard drive still provides a good combination of on-line capacity, speed, and cost making it ideal for desktop applications. However, the short data life and lack of removability make them poor choices when high capacity and long-term data retention are important.

CD Jukebox - Placing a CD-R drive into a robotic jukebox increases the available capacity, however, the added swap time only compounds the shortcomings in data rate.

M-O Jukebox - The additional near-line capacity provided by the robotics makes these systems viable solutions for many applications.

Optical RAID - By combining the performance and reliability aspects of RAID with the removability and data life benefits of magneto-optical disks, these systems improve on the advantages of a stand-alone M-O drive.

Magnetic RAID - The parallel nature of RAID provides enhanced throughput rates while the redundancy aspect increases the reliability of magnetic drives.

Tape Library - Adding an automatic media changer to a tape drive increases capacity but, due to the necessary swaps, access times are increased.

Due to the wide array of choices associated with each product type, it is difficult to generate a list of specifications for these devices. For example, M-O Jukeboxes are available in capacities ranging for 40 GB to 1 TB. However, our goal is to compare the various classes of storage devices not necessarily individual products within each class. Therefore, for each class of device, a midrange system was selected to represent the entire category and the following parameters were examined:

Specification	Description	Measurement Units
Capacity	The under head capacity (i.e., the storage capacity to which the system has access without swapping media).	Gigabytes (1 billion bytes)
Near-line	The storage capacity to which the system has access by swapping media. For removable media devices (marked with a *), ten additional sets of media are assumed.	Gigabytes (1 billion bytes)
Throughput	The sustained rate at which the system can write data to or read data from the storage device.	Megabytes (1 million bytes) per second.
Access Time	The amount of time the host has to wait to receive data after requesting it from the storage device.	Milliseconds
Swap Time	The amount of time necessary to change removable media. For removable media devices (marked with a *), an estimate for manually swapping the media is included.	Seconds
Data Life	How long the media can reliably store data. The data life for optical media is 30 - 100 years while that of magnetic media is only 5 - 10 years.	Years
Cost	The cost of the system normalized by the capacity. For removable media systems (marked with a *), the cost and capacity of ten additional media are included.	Dollars per Gigabyte
Power	The power requirements of the system normalized by the capacity.	Watts per Gigabyte
Size	The size of the system normalized by the capacity. For removable media systems (marked with a *), the size and capacity of ten additional media are included.	Cubic inches per Gigabyte
Weight	The weight of the system normalized by the capacity. For removable media systems (marked with a *), the weight and capacity of ten additional media are included.	Pounds per Gigabyte

The primary specifications for each storage device, based on a representative mid-range unit, are compiled in Table 2.

Table 2. Storage Device Specifications

	CD-R Drive	M-O Drive	Tape Drive	Magnetic Drive	CD Jukebox	M-O Jukebox	Optical RAID	Magnetic RAID	Tape Library	Units
Capacity	0.65	2.6	20	9.2	0.65	2.6	21	46	20	GB
Near-line	6.5*	26*	200*	0	130	270	210	0	280	GB
Throughput	0.6	1.5	1	8	0.6	1.5	6	32	1	MB/sec
Access Time	200	30	68000	10	200	30	40	20	68000	msec
Swap Time	30*	30*	150*	N/A	8	3.5	60	N/A	125	sec
Data Life	30	30	5	5	30	30	30	5	5	years
Cost	100*	88*	31*	130	120	120	140*	400	59	$/GB
Power	85	15	1.25	1.6	0.83	0.82	5.7	2.2	0.36	W/GB
Size	45*	16*	1.7*	2.5	98	140	24*	66	13	in^3/GB
Weight	0.68*	0.41*	0.06*	0.16	1.4	1.1	0.33*	0.65	0.19	lbs/GB

Using these specifications, a rating system was developed to normalize the numerical entries for each item. A scale utilizing the values 0 (worst) to 10 (best) was employed. The results of this line by line comparison are shown in Table 3.

Table 3. Storage Device Comparison

	CD-R Drive	M-O Drive	Tape Drive	Magnetic Drive	CD Jukebox	M-O Jukebox	Optical RAID	Magnetic RAID	Tape Library
Capacity	4	6	9	7.5	4	6	9	10	9
Near-line	5	7	9.5	0	9	10	10	0	10
Throughput	4	5.5	5	8	4	5.5	7.5	10	5
Access Time	7	9	0	10	7	9	9	9	0
Swap Time	7	7	5	0	9	10	6	0	5
Data Life	10	10	3	2	10	10	10	3	3
Cost	7.5	8	10	8	8	8	8.5	6	9
Power	3	5	8.5	8	9	9	6.5	8	10
Size	6	7	10	10	5	4	7	5.5	7
Weight	7.5	8	10	9	6	6.5	8.5	7.5	9

It is this Storage Device Comparison of Table 3 which will form the basis for the remainder of the analysis.

Document Imaging

Due to their relatively small file sizes (~50k), document imaging systems don't require high throughput rates. Certainly, access and swap times will have a greater impact on file retrieval time than data transfer rates. Similarly, since a large number of the small files will fit on each disk or tape cartridge, (under head) capacity is less important than the total near-line capacity.

In examining the remaining characteristics, we note that any of the candidate storage devices will provide sufficient data life for the average document life of three to seven years, Therefore, data life is not a major consideration. Of course, system cost is always a concern but not to the extent that it outweighs other factors. Of the remaining factors, the physical characteristics (i.e., size and

weight) are usually more important. Power requirements are not typically a factor except for very large systems.

We can summarize these requirements by applying a weighting factor to each specification listed in Table 3. A weight of 10 indicates that the associated characteristic is very important to the selection of the storage device while a weight of 0 means that the particular specification has no bearing on the selection.

Specification	Weight
Capacity	8
Near-line	10
Throughput	7
Access Time	10
Swap Time	10
Data Life	3
Cost	7
Power	4
Size	7
Weight	7

By applying these weights to the ratings of each storage device (as shown in Table 3) and normalizing, we generate a score for each device. This score reflects the ability of the storage device to fulfill the needs of the document imaging industry.

Storage Device	Score
Optical RAID	7.9
M-O Jukebox	7.6
M-O Drive	7.0
CD Jukebox	6.7
Tape Drive	6.7
Tape Library	6.3
Magnetic Drive	6.1
CD-R Drive	5.9
Magnetic RAID	5.7

The results indicate that devices in the magneto-optical storage class occupy the top three spots. The main advantages which these three devices have are:

1. Their ability to support large capacities, and
2. Their fast access and swap times.

However, there is still room for improvement. Any device which could offer larger under head capacity (thereby effectively reducing swap times by reducing the number of necessary swaps),

without sacrificing throughput or cost, would be readily accepted into the document imaging market.

Medical Imaging

Unlike document imaging systems, the medical imaging industry utilizes very large files; oftentimes reaching 100 MB or more. For this reason, throughput and (under head) capacity are primary concerns. Also, since data transfer will dominate the read/write times for these large files, access and swap times are less important.

Since the medical community is required to retain patient records beyond the life of the patient, data life is a very important selection factor. And, just like document imaging, cost is always a concern. Also as mentioned previously, size and weight seem to have more significance than power consumption.

Once again, these requirements can be summarized by assigning a weight to each specification.

Specification	Score
Capacity	10
Near-line	8
Throughput	10
Access Time	4
Swap Time	3
Data Life	10
Cost	7
Power	4
Size	7
Weight	7

As explained previously, the weights are applied to the characteristics of each storage device to determine which are the most suitable for this application.

Storage Device	Rating
Optical RAID	8.5
M-O Jukebox	7.5
M-O Drive	7.2
Tape Drive	7.2
Tape Library	6.9
CD Jukebox	6.8
Magnetic Drive	6.2
Magnetic RAID	6.2
CD-R Drive	6.1

Once again, magneto-optical class devices dominate the rankings but for a different reason. Here it is the data retention characteristic of M-O, along with its capacity, which make it desirable. Furthermore, Optical RAID has a demonstrable advantage due to its superior transfer rate. A new storage device which would provide larger capacity and/or faster throughput while maintaining at least a 30-year data life would be beneficial to the medical imaging community.

Characteristics of Optical Cube Memory

Based on preliminary information, 3-D Optical Cube Memory appears to have three highly desirable characteristics relevant to the storage sub-system market. Namely, data density, access time and throughput. As shown in Table 4, when viewed with respect to the dominant selection criteria of the document imaging and medical imaging markets, these are critical factors in the successful adoption of new storage technology in these industries.

Table 4. Summary of Weighting Criteria for Various Storage Applications

Specification	Document Imaging Weight	Medical Imaging Weight
Capacity	*8*	*10*
Near-line	10	8
Throughput	*7*	*10*
Access Time	*10*	*4*
Swap Time	10	3
Data Life	3	10
Cost	7	7
Power	4	4
Size	7	7
Weight	7	7

If 3-D Optical Cube Memory were weighed against the other selection criteria, it could be argued that the capacity of the media effectively eliminates the need for near-line storage. This greatly reducing or eliminating the swap time penalty. Therefore, if the Cost, Power, Size and Weight of the system can be made comparable to existing storage devices, 3-D Optical Cube Memory would fit easily into the document imaging market. Given similar circumstances for the medical imaging market, with a technology focus on assuring data retention for 7 to 30 years, the same holds true.

Conclusion

Although the data storage marketplace continues to change at a rapid pace, this preliminary analysis indicates there is a future in several markets for 3-D Optical Cube Memory. In order to better understand the application and acceptance of this technology, a development timetable vs. the product development cycle of the commercial storage industry would need to be performed. In addition, it would be advantageous to identify a target set of technical characteristics for the fist commercial application of the technology so that a more direct comparison can be made between the 3-D Optical Cube Memory and the demands and competition within the storage marketplace.

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